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PULSATING AURORA: LOCAL AND GLOBAL MORPHOLOGY

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PULSATING AURORA: LOCAL AND GLOBAL MORPHOLOGY

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ABSTRACT

Pulsating describes a low-intensity aurora that undergoes rapid alternating increases and decreases of luminosity. Extensive new data available from ground-based low-light-level television cameras and satellite scanners have allowed a much more detailed study of pulsating aurora than previously possible using photometer and all-sky data. Intensity variations in pulsating aurora may be repetitive, quasi-periodic or occasionally periodic with a time scale ranging from a second to several tens of seconds. Pulsations occur in auroral arcs, arc segments and patches of fixed or variable area during the lifetime of a single pulsation. The temporal and spatial characteristics are highly variable over a broad and continuous spectrum; rapid changes from one set of characteristics to another frequently occur as do reversible changes from pulsating to non-pulsating auroras. Diffuse, slowly pulsatng arcs occur in the evening sector immediately before and after the passage of the westward traveling surge. In the midnight sector, both arc segments and patches occupy a broad region behind the westward traveling surge. Poleward-stretching torch-like structures containing pulsating patches and arc segments are often observed at the poleward boundary of the diffuse auroral oval in the midnight sector.

A narrow region of pulsating patches and arcs occupies the morning sector, with the arcs generally located at the poleward boundary. Newly identified here is a 2 to 4 Hz high-frequency modulation, of unknown cause, that appears in more than 50% of all pulsating auroras in the midnight and morning sectors, the amplitude of the modulation ranging up to 20%. It is suggested that a characteristic limit on the maximum intensity observed in pulsating auroras is associated with strong pitch-angle diffusion. A diffuse background luminosity is observed in association with pulsating aurora. It is concluded that this background is crucial in the explanation of pulsating aurora as well as the bright auroral forms that on occasions form on field lines previously occupied by pulsating forms.

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CHAPTER 1

INTRODUCTION

> "However, it is true of northern lights as of many other subjects of which we have no sure knowledge, that thoughtful men will form opinions and conjectures about it and will make such guesses as seem reasonable and likely to be true."
>
> (Kongespeilet. A thirteenth-century Norwegian chronicle.)

It seems to be fairly well established that the aurora is caused by electrons and protons originating in the sun. These particles are thought to enter the earth's atmosphere through largely unknown electrodynamic and magnetohydrodynamic processes. In the book "De Magnet", Gilbert (1600) described the first scientific work related to the "aurora borealis". His most important contribution was to recognize the earth as a great magnet.

The geomagnetic field, out to a few Re (earth radii), can be fairly well represented by an eccentric dipole with its axis deviated by 11° from the earth's axis of rotation. However, at a greater distance, the geomagnetic field is disturbed by the solar wind. A shock front facing the sun, and a magnetic tail in the direction away from the sun are formed. The shock front is situated at a distance of 8 to 15 Re, depending on solar activity, whereas earth-orbiting spacecraft have shown that the tail is still well-defined at 80 Re and present at a distance of 500 Re.

The solar wind particles appear to be coming in to the inner magnetosphere through the plasma sheet in the magnetic tail. These particles are believed to be accelerated by unknown mechanisms and dumped into the upper atmosphere along the boundary of closed field lines.

When hit by the incoming particles, the atmospheric atoms and molecules are excited. By returning to a lower state or the ground state, the molecules and atoms emit light which is observed as aurora.

The auroral light is composed of several frequencies corresponding to the energy difference between quantum energy states of the molecules or atoms involved, N_2, N_2^+, O_2, N, and O being the most important constituents at auroral heights. The atoms give single line spectra corresponding to pure electron transition, while the molecules form band systems due to combinations of vibrational and rotational quantum states.

Aurora occurs primarily in boreal and austral auroral ovals. These ovals are located at a distance of about 23^o-25^o from the poles at the night side, and approximately 15^o

at the day side, during moderate magnetic activity. They are thought by some to correspond to the boundary between open and closed magnetic field lines at auroral altitudes.

The interaction between precipitated particles and the upper atmosphere gives rise to a multitude of structures called auroral forms.

In past years a rather elaborate classification scheme was developed to categorize the different forms according to their shape, intensity, internal spatial structure and temporal variation of the whole form or parts of it. Certain auroral forms exhibit periodic or quasi-periodic temporal variation; Such auroras are listed in the International Auroral Atlas (1963) by use of the term "pulsing". There it is stated that pulsing describes a condition of fairly rapid, often rhythmical fluctuations of brightness. The period of fluctuation ranges from a fraction of a second to several minutes. Listed sub-classifications are described by the terms pulsating, flaming, flickering and streaming. One of these sub-classes, pulsating auroras, is the subject of this thesis.

Motivation for the detailed study of pulsating auroras exists for several reasons. One is that the periodic behavior itself must surely provide a hint to the understanding of the causitive mechanisms, thus there is hope that one might quickly get to the cause of at least this one type of aurora. More important is the fact that pulsating auroras constitute a major part of the observed auroral display. If one distinguishes between pulsating and non-pulsating auroras and then integrates over time and space, the result is likely to be that the pulsating auroras are as common, if not more common, than all other types of auroras.

The areal extent of the pulsating portion of the auroral display is large and the duration of the display is long. Furthermore, the total deposition of energy into the ionosphere within the region of the pulsating aurora is greater overall than in other parts of the display. (The energy deposition rates in other types of aurora frequently exceed that in pulsating aurora, but these regions are temporally and spatially restricted.)

Pulsating aurora is the most common type of aurora in the morning sector and, apart from the brief expansion phase of the auroral substorm, it also dominates the midnight sector. It continues throughout the extended recovery phase of the substorm, sometimes lasting for hours. Pulsating aurora shows close association with such other phenomena as radio wave absorption, bremstrahlung X-rays, negative bays in the magnetic field and magnetic pulsation phenomena.

Nevertheless, little is known about pulsating aurora. Visually less spectacular and harder to study with available techniques, pulsating aurora has remained even more a mystery than other types.

Two new instrumental techniques now permit investigation not previously possible. One is the development of the all-sky television which allows the acquisition of auroral photographs at a rate of 60 per second and showing a region several hundred kilometers across at auroral altitude. The other is the high-resolution satellite scanner technique providing images of major portions of the auroral regions as seen from above at the rate of one per hundred minutes. Data from these new sources together with data in the form of magnetic records, magnetic indices, conventional all-sky camera films and narrow-field television records are used in this thesis.

The principal objective here is to obtain an improved morphological description of pulsating aurora. Secondary objectives that necessarily follow after the primary effort are to examine the relationships between pulsating aurora and other phenomena and to go as far as possible toward seeking the causitive mechanisms of the pulsating aurora.

CHAPTER 2

OBSERVATIONS ON PULSATING AURORA

As yet there has not been any comprehensive study of the global characteristics of pulsating aurora although several studies have given information on the large-scale aspects of the phenomenon. Others have concentrated upon the temporal variations within small segments of the pulsating part of the auroral display and on the small-scale structural aspects. Still other studies involved analysis of the phenomenon statistically in relation to other such variables as, frequency, geomagnetic latitude, height, magnetic activity and local time.

Much of what is known in a general way comes from visual observation of pulsating aurora. The dark-adapted human eye is a rather good instrument for observing pulsating aurora because it can recognize both temporal and structural characteristics of this complex phenomenon. There is, of course, serious limitation owing to the inability to record adequately what the eye sees and to make quantitative measurements of temporal variations.

Photometric observations do allow precise measurement of temporal variation and of intensity as a function of wavelength. However, the complete inability to detect structured characteristics and to distinguish between true temporal and spatial variations is a serious limitation. In some cases this difficulty has been partially surmounted by using arrays of two to four narrow-field photometers. Photographic all-sky cameras acquiring photographs at the rate of 1 per minute have helped to delineate the regions where pulsating auroras occur but the temporal resolution has been too low to obtain quantitative information on the temporal characteristics of the phenomenon. Narrow-field-of-view television observations used in recent years eliminate most of the limitations of other methods but are inadequate to observe certain of the intermediate-scale characteristics that now seem significant.

Previous definitions of pulsating aurora have stressed the point of quasi-periodic intensity variations. Omholt (1971) described pulsating aurora as "aurora with approximately stable geometry which shows more-or-less rhythmic variations in intensity of all parts of the form varying approximately in phase".

Likewise, Cresswell (1968) claimed that patches, except for gradual changes, can maintain their shapes and drift velocities for long periods while they pulsate quasi-periodically.

The Photographic Atlas of Auroral Forms (1951) distinguishes between "pulsating arcs" and "pulsating surfaces" describing both forms as rhythmically appearing and disappearing in the same place with a period of several seconds.

Pulsating aurora occurs most often in the latter part of the night (Omholt, 1971). A study by Heppner (1954) showed that pulsating aurora occurs most frequently at low auroral zone latitude, and Cresswell (1968) found that pulsating auroras are restricted primarily to the equatorward boundary of auroral displays in the midnight and morning sectors. Campbell and Rees (1961) and Omholt and Berger (1967) also concluded that pulsating aurora occur between magnetic midnight and dawn. However, Störmer (1955) reported observations of stable, slowly pulsating arcs in the early evening sector. This is believed to be the only reported such observation prior to this work.

Kvifte and Pettersen (1969), from their comprehensive study of the morphology of pulsating aurora, found that pulsations occur in a more-or-less spiral-shaped region or part of an oval. This oval expands equatorwards when magnetic activity increases.

In the morning sector a variety of displays of pulsating aurora have been observed (Cresswell, 1968). The display may extend several hundred kilometers in the north-south direction and several thousand kilometers in the east-west direction, showing mainly diffuse pulsating patches but also, at times, pulsating arcs (Cresswell, 1968).

The pulsating phase of the display often lasts for several hours although it is composed of numerous short sequences of pulsations lasting from a few seconds to several tens of minutes (Cresswell and Davis, 1966). Generally, pulsating aurora has been considered to be a morning sector phenomena, but there has been little description of the spatial extent of the pulsating auroral region, its shape, and the location of the region's boundaries. Little is known about the shape of pulsating auroral forms although it is generally agreed that they can be divided into two groups--arcs and patches. Patches are the most common pulsating structure, but arcs are also quite often pulsating (Cresswell, 1968). Cresswell made the only known attempt to describe pulsating forms in any detail. He found that the size of pulsating patches ranged from approximately ten to a few hundred kilometers across. He was, however, not able to arrive at a classification scheme for pulsating patches.

Both eastward and westward drifting patches have been observed, occasionally in the same display (Cresswell, 1968). The eastward drift is the most common. Its speed is typically a few hundred meters per sec.

Heppner (1954) related pulsating aurora to magnetic disturbances of negative bay type. He determined the following simple pattern of auroral activity during the night: Homogeneous arcs and small positive magnetic disturbances in early evening followed by rayed arcs and bands in the late evening. Breakup into active forms occurrs near midnight and is associated with large negative disturbances. Diffuse pulsating patches and arcs are observed in the morning sector until twilight at the time of recovery of negative disturbance. Pulsating auroras occur when the local horizontal magnetic field component is strongly negative or recovering from a negative bay (Cresswell, 1968). Omholt (1971) states that pulsating aurora is "a typical post-breakup phonemonon in the auroral display". Kvifte and Pettersen (1969) found that during high magnetic activity the pulsation amplitude starts at a moderate intensity value around local magnetic midnight followed by a rather sudden increase to a constant intensity level near 10 kR in 4278 Å. In their study they also found that the sudden increase in intensity occurred gradually later at night at higher latitude.

Pulsating aurora has been viewed as aurora with approximately stable geometry, showing more-or-less rhythmic variations in intensity. An expression for the intensity as a function of space and time was given by Omholt (1971):

$$I(\bar{r},t) = I_S(\bar{r},t)\ I_T(t)$$

He assumed that $I_S(\bar{r},t)$ varies slowly with time compared to $I_T(t)$. Then $I_S(\bar{r},t)$ describes the slowly varying geometry of the aurora, whereas $I_T(t)$ represents the pulsations.

An investigation of pulsation frequency by Johansen and Omholt (1966) shows that Fourier spectra of pulsations usually peak around 0.05-0.15 Hz. The power falls off rather sharply at frequencies higher than 1 Hz. This fall-off may be due to the velocity distribution of the precipitated particles and not to the mechanism itself.

Kvifte and Pettersen (1969) found that there was a tendency for shorter periods to occur later in the night. Omholt and Petersen (1967) oppositely stated that higher frequencies are more dominant in the early night than in the morning hours. Usually pulsations are fairly irregular, but in some rare cases they may be more regular and even sinusoidal (Johansen and Omholt, 1966). The amplitude and Fourier spectrum may remain fairly constant for periods of several minutes, even when the pulsations are fairly irregular (Omholt, 1971).

Cresswell (1968), using a TV technique, studied different kinds of time variations in pulsating aurora quite extensively. He concluded that pulsating patches fall into two main categories; those in which the growth and decay phases are simultaneous over the entire form, and those in which they are not simultaneous. The latter form results in apparent motion and changes in size and shape of the auroral forms. He also concluded that different patches commonly pulsate asynchronously.

Also according to Cresswell (1968), a diffuse background of several kR of 4278 Å emission invariably accompanies pulsating auroral displays. The pulsations are superimposed on this and are easy to recognize if their intensity fluctuates from this level to a maximum and down again. The intensity variations are of the order of a few kR or less, and very rarely exceed 10 kR in 4278 Å. This description agrees fairly well with that of Omholt (1971) who stated that pulsations in the frequency range 0.01 to 10 Hz, usually have an intensity of 1-2 kR or less as measured in 5577 Å or 3914 Å.

Campbell and Rees (1961) studied the correlation between auroral pulsations and magnetic micropulsations in the period range 6 to 10 sec. Peak-to-peak correspondence between light pulsations and magnetic micropulsations was found for about 60% of the time that auroral pulsations appeared. This is a high correlation considering the different weight functions of a photometer and a magnetometer.

Also, X-ray pulsations seem to be closely related to auroral pulsations. Rosenberg et al. (1967) observed simultaneous pulsations in aurora and X-rays in a typical event of pulsating aurora. Berkey (1974) found a temporal correlation of the pulsating aurora and increased radio wave absorption, and concluded that the two phenomena are directly related.

From Carl Störmer's data, Egeland and Omholt (1966) found that pulsating arcs and patches show little or no height variation with latitude, the height being close to 100 km. There is evidence from Doppler temperature measurements, however, that the height of the aurora may vary during intensity fluctuations, it perhaps being lower during the period of increased intensity (Hilliard and Shepherd, 1966). This apparent height variation indicated to them that the pulsations in auroral light are caused primarily by changes in the electron energy spectrum, rather than solely by changes in the total electron flux.

Shepherd and Pemberton (1968) found the brightness fluctuation to result from enhancement of precipitating electrons in a broad energy region located near 15 kev which again indicates a low-altitude location of the pulsations. However, pulsating surfaces are, according to Egeland and Omholt (1966), distributed over a broader height interval than pulsating arcs.

CHAPTER 3

INVESTIGATIVE METHODS AND SOURCES OF DATA

3.0 Introduction

With several exceptions, nearly all previous studies of pulsating aurora have been statistical in nature. In most of these studies, photometers have been the main instrument for collecting data. There are, however, severe limitations on the information that can be extracted from photometer data. Spatial variations cannot be recorded unless a meridian or other scanning photometer is used, in which case temporal information is traded for a spatial intensity profile. Likewise, motion of auroral forms may show up as intensity variations. An example is provided by fast rays in auroral arcs. When moving across the field of view of the photometer, the rays may be interpreted as temporal pulsations on the photometer recording, or pulsations may not be recognized because the real pulsations do not appear in what is believed to be a pulsating portion of the display. In essence, photometric observations alone do not unambiguously permit determination of whether a particular auroral form is pulsating or not.

Similar problems exist in interpreting the data taken by other methods. All-sky pictures, for instance, give very little information on short-time changes and only marginal information on fine structures in the auroral display.

With respect to television, there seems to be only one major disadvantage. With the data available so far, it is not generally feasible to make accurate or absolute intensity measurements. The time resolution is adequate, and by using both the narrow-field and the all-sky television cameras simultaneously, one we can get excellent coverage over the whole sky and, at the same time, study the fine structures of the pulsations. The usefulness of the simultaneous observation will be evident later.

By use of simultaneous television and DMSP data, one can learn to recognize certain features of pulsating aurora which may be used to identify them in regular all-sky camera data. These data then may be very well suited for studying drift patterns and slow (>10 min) variations in the geometry of pulsating aurora.

This study is based mainly on television data, but it also uses additional data where these can give new information that could not have been obtained from television data.

3.1 Instrumentation

The main bulk of the data presented in this work has been obtained by the use of image orthicon television cameras (Davis, 1966) and also from DMSP satellites (Pike and Whalen, 1974).

Television for auroral study has a major advantage over photometers and other observation techniques presently used in that it distinguishes between temporal and spatial variations. The cameras used here are low-light-level image orthicon (IO) television cameras. With a sensitivity comparable to an ASA rating of 10^7, they are far more sensitive than most other image-producing devices presently in existence. The IO tube consists of an image section where the incoming photon hits a photocathode and releases an electron. This primary electron is accelerated by a high electric field. Then the electron strikes a target and ejects several secondary electrons. A fine mesh close to the target collects the secondary electrons leaving the target positively charged in areas corresponding to higher incoming light levels. The target is scanned by a returning electron beam which is modulated by neutralizing the positive charge. By mulitplying the signal carried by the returning electron beam and adding synchronization pulses, a signal is produced that can be used in a commercially available television monitor. With an interlaced scan every 1/60 of a second, an entire frame is produced every 1/30 of a second. The television signal is recorded on 1" video tape. In this study, three different lenses were used to obtain data. The fields of view (FOV) were 12 x 16°, 140° circular and 180° circular. Data taken with the 12 x 16° FOV will be referred to as "narrow-field" data, while data from the two latter FOVs will be referred to as all-sky data, irregardless of whether it is 140° or 180°. Most all-sky data, however, were taken with the 140° lens. The camera was pointed straight up to give a view of the whole sky down to approximately 20° above the horizon. At the hundred kilometer level, this corresponds to a circle with a radius of 250-300 km. The distortion in the picture is quite large, and the calculation of distance is therefore not very accurate unless a quite complicated technique is used. The spectral response of the TV cameras is in the range 4000 Å and 7000 Å with a maximum at 4500 Å.

By a combination of three TV cameras with different optical filters--red, green, and blue--a color image of the aurora is assembled. Color TV was used both with narrow-field lenses and with 140° all-sky lenses.

Intensity recordings were obtained by use of an electronic analysis device that measured the integrated electric signal corresponding to a determined position on the television screen on successive frames. This has replaced the photocell used in earlier works. The rectangular area over which the signal was integrated will be referred to as the "window".

The size and location of this window could be changed to fit the location and shape of object of interest. The continuous chart recording is made of the voltage pulse from each frame, but due to the high frame rate, 60 per second, it shows up as a continuous recording.

Photographs taken of the TV screen for purposes of illustration were usually exposed for 1/4 second. This exposure was desirable in order to reduce the noise level to approximately that of visual observations of the TV screen.

One serious limitation to the television system is the poor information about absolute intensities. Because of this, a uniform structure which fills the whole field of view may not be recognized at all because of the lack of contrast. Nevertheless, use of the analysis device on video-taped data does result in a linear measurement of intensity so that relative measurements are possible.

Defense Meteorological Satellite Program (DMSP) satellites have been introduced to auroral studies during the last few years. They have made possible the first high resolution pictures of large parts of the auroral oval. There are several different DMSP satellites, but data from only two of them have been used here.

DMSP satellite No. 5528 has a near-polar orbit, oriented in the noon-midnight meridian. DMSP satellite No. 7529 also has a near-polar orbit, but it is oriented along the dawn-dusk meridian. The pictures are generated by scanning the region below the satellite as it moves in its orbit. Both satellites have an orbital period of 101 min. This means it takes the satellites from 15 to 25 minutes to travel a distance comparable to the size of the auroral oval, a time also comparable to the entire expansive phase of an auroral substorm. It takes the satellites approximately two minutes to travel a distance comparable to the diameter of the field of view of the all-sky camera. The horizontal speed of the satellite is 6-7 km/sec which is comparable to some of the motions in the auroral display. With a scanning rate of 2 per second, each scan line is approximately 3 km wide. This is reasonably good resolution even though the most narrow auroral forms have a width of 100 m or less.

The width of the photographs perpendicular to the motion of the satellite is approximately 2500 km at the 100 km altitude (Pike and Whalen, 1974).

The spectral response of the detectors are peaked between 6000 and 8000 Å with half response at 4500 Å and 11,000 Å.

It has been suggested that a pulsating form would show up in a DMSP image with alternating bright and dark regions due to the interaction between the horizontal speed of the satellite and the temporal brightness variation in the form. Some examples of alternating bright and dark regions have been identified, but they are believed to be caused by noise in the satellite detectors. This conclusion is based on the fact that such lines show up in only a few of the DMSP images. When they do, there does not seem to be any discrimination between patches that are believed to be pulsating and bright arcs that most certainly are not pulsating.

Although few data from the all-sky camera are presented in this work, such data were used quite extensively in its preparation. An all-sky camera system consists of a 16 mm camera which can be run in a single frame mode and two mirrors, one plane and one convex. The camera looks up through a hole in the convex mirror. In the plane mirror it can see the image of the whole sky in the convex mirror. The 16 mm format does not give an adequate resolution to allow a detailed observation of the aurora, but it is sufficient to give information on large-scale forms like arcs and patches.

With a picture rate of one per minute the all-sky film is ideal as a means of getting an overall view of a whole night's auroral activity. Projected at a rate of 24 frames per second, the all-sky film gives useful information on slow changes in forms and changes in drift directions, as when changing from westward to eastward.

3.2 Sources of Data

In the preparation of this thesis, systematic examination of several years of data have been performed to learn the characteristic features of pulsating aurora. The data examined include:

All-sky camera film from Byrd Station, and Amundsen/Scott (South Pole) Station, Antarctica, in the period May 20-August 1, 1960, May 20-August 1, 1964 and May 20-August 1, 1965.

All available DMSP data for the northern winter season 1972-1973 and 1973-1974, which amounted to several hundred passes from each season. All available narrow-field and all-sky television data from College during the winters 1972-1973, 1973-1974 and 1974-1975. This amounted to approximately 100 hours of data from each observing season. In addition to the above, all-sky data from Ester Dome and Fort Yukon were used on some occasions.

Television data were recorded only when some kind of aurora was visible and mainly during the appearance of active forms such as active arcs, breakups or pulsating aurora. Roughly half of the television data show pulsating aurora in one form or another.

Universal time has been used consistently throughout this work, and no reference is made to local time or local geomagnetic time. Local geomagnetic midnight has been referred to occasionally and occurs around 11:30 UT.

A large portion of the television data utilized was obtained by others. However, the author participated in, or was solely responsible for, the collection of a substantial portion. His interest led to collection of a relatively high proportion of recordings of pulsating aurora during the 1972-1973, 1973-1974 and 1974-1975 observing seasons.

It is unlikely that one person has ever before examined such an extensive data set pertaining to pulsating aurora.

CHAPTER 4

PRESENTATION OF DATA

4.1. Definitions of Pulsating Auroral Forms

The observations made in this study suggest the introduction of a new definition of pulsating aurora based upon two crucial characteristics that together distinguish a pulsating form from all other types of aurora. A pulsating auroral form is one with low maximum intensity and a fast alternating increase and decrease in intensity over at least one full cycle. The maximum intensity level typically is a few kR in 4278 Å; the increase in intensity from a minimum to a maximum is typically of the order of 0.1 to 1.0 sec and rarely exceeds 15 seconds. Usually the change in intensity passes through the detection threshold of the dark-adapted human eye or of a highly sensitive imaging system. Because the human eye is insensitive to intensity changes at light levels just above detection threshold, a pulsating aurora generally gives the visual impression that the form is blinking on and off.

This general definition of pulsating aurora differs from all previous definitions in which a quasi-periodic nature and the spatial stability of the forms has been taken as a characteristic of pulsating aurora. However, neither the quasi-periodic behavior or the spatial stability are common characteristics of all pulsating forms nor are they distinguishing characteristics.

Pulsating aurora can take on a multitude of forms, simple and complicated, and its occurrence in the framework of the auroral substorm or in the context of the global distribution of the aurora is more complex than earlier thought.

The complexity of the problem in detailing a morphological description of pulsating aurora is illustrated in Table 4.1, in which the various characteristics relevant to the description of pulsating aurora are listed, together with the behavioral domain each characteristic occupies.

There is an intricate and highly-variable interlinking between the various characteristics at any one time and location as to nearly preclude subdivision of pulsating aurora into distinct subtypes. Within each type there are great ranges of characteristics that are highly variable and with continuous gradation.

4.2 Eastward Drifting Pulsating Patches

A natural starting point of a description of pulsating aurora is a discussion of eastward drifting pulsating patches because it is the one most commonly referred to in past literature. This type of pulsating aurora is the simplest one observed, both in form and in temporal variation. The one common characteristic distinguishing this form of pulsating aurora from all other pulsating aurora is the steady eastward drift.

During a display of eastward drifting pulsating aurora at the latitude of College, the whole sky is usually filled with fairly large patches. To the eye, or on an all-sky picture, these patches look almost homogeneous over their entire area which is normally

TABLE 4.1

Characteristics of Pulsating Aurora

Characteristics	Domain
Spatial stability	Stable (fixed area)--Streaming (growing area)--split-streaming
Shape	Patches--arc segments--arcs
Size	10 km - 200 km
Repeatability	Single pulse--repetitive--quasi-periodic
Periodicity	High-frequency modulation (2-4 Hz)--Pulsation (1 - 0.05 Hz)
Intensity (4278 Å)	1/2 kR - 10 kR
Background	High-low intensity, uniform, structured
Sector	Evening-midnight-morning-day until noon
Drift	Eastward or westward
Speed of Drift	0 - 1 km/sec
Substorm time	Expansive phase--recovery phase
Global location	Diffuse auroral oval
Relation to Omega Bands	South of omega band forms, northern boundary when exists
Latitude	$\sim 60°$ to $68°$

from 20 to 200 km across. Also the pulsations are semi-periodic or repetitive with periods generally ranging from 2 to 20 sec, with some periods as short as 1 sec observed on rare occasions. The eastward drifting pulsating patches occur in the morning sectors of the auroral oval.

One typical example of eastward drifting patches is shown in Fig. 4.1, A and B (see also Fig. 4.2). The two patches shown here are from January 26, 1974. In the intensity recording of the all-sky TV data, Fig. 4.1C, there is an interesting 7-8 min periodicity. The $\sim$5-min long envelopes are due to several patches drifting across the analysis window in which the integrated intensity is recorded. The almost-periodic 7-8 min variations resulted from the even spacing between patches drifting east; that is, they result from motion rather than actual pulsation. Periodic pulsations ranging from 1 to 10 sec in period are observed within these patches. The amplitude modulation is variable within a patch, and not all the modulation can be considered periodic or semi-periodic. A high degree of modulation is observed in these pulsations most of the time. Examples of sudden changes in both frequency and pulsation amplitude appear near 15:26:45 UT and again later at 15:28:25. At 15:28:53 one patch suddenly faded and disappeared.

High-frequency modulation, a 2-4 Hz low amplitude modulation of the main pulsation (see Section 4.8), is evident in the original TV data, but due to the large area of the analysis window used to obtain the traces shown in Fig. 4.1C and the low time resolution, it does not show up well in the figure. At 15:33:50 and 15:33:55 two single pulsations occurred. This is one of the few times when such very short flashes were observed. Each of them lasted for 12-14 frames, or approximately 0.2 sec.

Streaming, a simultaneous spatial and time variation of intensity (see Section 4.6) did occur in the interval portrayed by Fig. 4.1C, although it was not a dominant feature in these patches. The two pulses appearing near 15:24 were the result of streaming into the window while the more stable region of the patch was still outside.

The geometry of these eastward drifting patches is, in general, very stable. The observed forms are due to horizontal extent and are not caused by vertically extending sheets. Such individual patches can last for 10-15 min as they drift slowly across the sky from west to east while pulsating. Changes in geometry may be so slow that the same patch is easily recognized in two pictures taken as much as 10 min apart.

In general, the shape of eastward drifting patches is fairly simple, usually showing a continuous outwardly convex boundary. With a dimension of 20-200 km across and a near uniform intensity variation, the eastward drifting patches are easily recognized by a visual observation of the data. Modulation is usually fairly high--50% to 100%. Here, 100% modulation refers to cases where the intensity drops down to the background level during the "off" periods, regardless of whether or not there is a background of more-or-less stable aurora. If such a background exists, a photometer will record less than 100% modulation. The maximum intensity of the eastward drifting patches has not been specifically measured in this work, but both television and photometry observations show that it is typically a few kilorayleigh (kR) and probably never exceeds 10 kR in 4278 Å (Cresswell, 1968).

The pulsating period of eastward drifting patches varies from 1 to 20 sec with a peak in the distribution between 5 and 10 sec. Patches may suddenly appear or disappear, but more often they develop gradually from a small weak form to a maximum size and intensity, the growth continuing through several "off-on" cycles. They eventually disappear by slowly fading, all the while pulsating on and off.

Sudden changes in frequency or pulsating amplitude, are common within this type of pulsating aurora.

Some measurements of the eastward drift-velocity of pulsating patches have been obtained from the all-sky television data. Due to the inherent difficulties in accurately locating the drifting form, the measured drift suffers from a substantial uncertainty. The distance drifted in each case was calculated on the basis of a star chart with the assumed altitude of 100 km. The assumption that the drifting forms are located at 100 km altitude may be in error by as much as 20 km but this will not seriously affect the velocities which are determined.

For these measurements the error in look-angle, representing the uncertainty in the location of the form, is estimated to be 2^{o} or less for each individual observation. Thus, the error in the distance over which the velocity is measured is less than 6 km if the look-angle is within 25^{o} from zenith. The error in the velocity depends on the time increment involved in the observation and is least if the observed form is drifting slowly.

One example of a patch drifting from west to east is shown in Fig. 4.2. That patch is one that gave rise to part of the pulsations in the intensity recording in Fig. 4.1C, more specifically, the part starting around 15:24 and lasting until 15:29 on January 26, 1974. The patch showed a stable geometry as it drifted through the field of view of the all-sky TV. The trailing edge, in particular, kept its shape for several minutes and this edge was used in the drift measurement. The measured drift velocities between locations in the four pictures were from

a-b	34 km/132 sec - 260 m/sec
b-c	12 km/70 sec - 170 m/sec
c-d	14 km/64 sec - 220 m/sec

and from

a-d	60 km/266 - 230 m/sec

with the most accurate measurement being

230 ± 25 m/sec .

Several other measurements were also made in the same manner. In each case, within the limit of uncertainties, the drift was found to be nearly constant over the observing period. Measured drifts to the east, including the one already described, are as follows: 100 ± 40, 210 ± 25, 230 ± 25, 450 ± 30 and 330 ± 20 m/sec.

4.3 Westward Drifting Patches and Arc Segments

Westward drifting pulsating forms in the midnight sector show much more variation in spatial structure and temporal change than do eastward drifting patches. The behavior of eastward drifting patches is generally singular in nature and generally unchanging with time, but in westward drifting pulsating structures there is a continuous spectrum of forms between patches and arcs with a greater overall variability in behavior.

Figure 4.3 shows typical examples of intensity recordings of westward drifting patches. The durations of the pulses seen in Fig. 4.3 vary from 2 sec to 5 sec. The variations are sometimes irregular and at other times almost periodic. High-frequency modulation appears in the data and is strongest between 11:09:51 and 11:09:58. The temporal behavior shown in Fig. 4.3 is characteristic of the westward drifting patches and arc segments.

Both westward drifting patches and arc segments at times show very complicated structures. Patches, as well as arcs, exhibit different types of internal structure. The most common is the diffuse form with uniform brightness throughout and ill-defined edges. In such forms the pulsating temporal variation is uniform over the whole patch unless the form is streaming (see Section 4.6).

In addition, some westward drifting structures exhibit uniform brightness and sharp edges; these forms may have quite complicated shapes. Two or more forms may be matched together as in parts of a jigsaw puzzle and be separated only by a narrow region of low background emission.

Finally, some patches show internal structures consisting of semi-parallel filaments. In these forms, slow pulsations are uniform over the whole patch whereas high-frequency modulation, if it occurs, is uniform only over individual filaments. The size of the westward drifting patches and the length of the westward drifting arc segments generally varies from a few kilometers to several hundred kilometers, while the width of the arc segments is usually on the order of a kilometer or less. Although the sizes of westward drifting patches are generally constant throughout a display, the frequencies of the pulsations in adjacent patches of the same size may be quite different. The intensity of westward drifting forms is similar to that of eastward drifting patches, generally a few kR in 4278 Å. Modulation amplitude is high, mostly between 50 and 100%. Most westward drifting patches and arc segments grow in area during the growth phase of each pulse; this phenomenon, termed streaming, is described in Section 4.6.

There does not seem to be any difference in pulsating frequency between patches, arc segments or arcs when they are present in the same display. However, the frequency increases slightly with increasing activity and ranges from 0.1 Hz to 1 Hz, the most common frequency being 0.2-0.5 Hz. High-frequency modulation is also common in the westward drifting forms, both in patches and arc segments. Unlike the eastward drifting patches, westward drifting forms are usually very unstable and may change shape enough between two pulses to prevent recognition of whether the form is continuing to exist or a new form has developed.

Westward drifting pulsating patches and arc segments are located in the diffuse auroral oval in the midnight sector. The arc segments may be aligned in any direction. However, all arc segments appearing within one region of the display at one time are aligned parallel to each other.

Measurement of the westward drift velocity by the technique described earlier, yielded values ranging from 250 m/sec to 1150 m/sec. Recall that the eastward drifting pulsating patches generally drift much slower, in the range 100 m/sec to 450 m/sec. College, Alaska, is located at 64.5° latitude and moves from west to east with a speed of 200 m/sec relative to the sun-earth line. Adding this velocity to the eastward and subtracting from the westward velocities gives a westward velocity ranging from 50 m/sec to 950 m/sec and an eastward velocity ranging from 300 m/sec to 650 m/sec relative to the earth-sun line. Consequently, it appears that the mean drift velocity is approximately the same in both directions away from the sun-earth line. However, the drift to the west shows more spread in the velocity than does the eastward drift. Furthermore, viewing of fast projections of all-sky film from Byrd Station, Antarctica gives the impression that the drift is much more irregular to the west than to the east.

4.4 Pulsating Arcs

Pulsating arcs occur mainly in the morning sector, but can also appear in the evening and midnight sectors during the late recovery phase of a substorm. These arcs are always aligned east-west and located at the poleward boundary of the diffuse auroral oval. With a length of several thousand kilometers, these arcs usually stretch from one horizon to the other as seen from a ground-based location.

Figures 4.4 and 4.5 show two typical examples of pulsating arcs. In these arcs, the period of pulsation is relatively stable and ranges mainly from 5 to 10 sec. Shorter periods, down to 1 sec, also occur but are less frequent. In Fig. 4.4, around 12:23:55, there are several rapid pulsations, an observation which again underlines the fact that a pulsating form may change frequency very suddenly. The intensity traces are in each case from the most active part of the display.

Pulsating arcs are initially formed by a recombination of patches and arc segments in the late recovery phase of an auroral substorm. There are two basic sub-types of pulsating arcs--diffuse pulsating arcs and discrete pulsating arcs. The diffuse arcs are broad bands of uniform luminosity with diffuse edges and width of order 10 km. Usually only one or two are visible at a time in an auroral display, and each arc pulsates only a few times before it disappears. The pulsating period of these diffuse arcs ranges from 5-20 sec. High-frequency modulations are frequently observed in them. There is usually a fairly strong background in the vicinity of the diffuse arcs.

Discrete pulsating arcs are narrower and have more sharply defined boundaries than diffuse arcs. The width is a few hundred meters or less. Discrete pulsating arcs occur in a band of multiple arcs. This band is not superimposed on a diffuse background, although such a background usually exists in the vicinity of a discrete arc system.

The pulsating frequency in these arcs is usually high and comparable to the fastest pulsations observed in patches. The pulsation period ranges from 1 to 5 sec although longer periods have been observed on some occasions.

The maximum intensity observed in both discrete and diffuse pulsating arcs is close to the maximum intensity in pulsating patches and is typically a few kR of 4278 Å emission. Both discrete and diffuse pulsating arcs have been observed in the same display, but in different spatial regions. They are located at the poleward boundary of the diffuse auroral oval in the late recovery phase of an auroral substorm.

4.5 Pulsating Arcs Before Breakup

On February 16, 1975, 09:55, pulsating diffuse arcs formed south of a stable, bright arc. The preceding 2-3 hours had been quiet as judged by the College magnetogram and the College and Fort Yukon 16 mm all-sky film. No magnetic or auroral activity other than the diffuse quiet arc was observed prior to the formation of these pulsating arcs. Breakup of the quiet arc occurred at 10:12 and the surge that developed disrupted the pulsating arcs, which at this time turned into pulsating patches. This display occurred less than two hours before magnetic midnight, and it is uncertain whether it happened in the late evening or in the early midnight sector. Similar displays of pulsating arcs being broken up by the westward traveling surge have been observed in early evening sector. However, in these situations the magnetic activity has been much higher, and it may be argued that these pulsating arcs were remnants from an earlier substorm and not associated with the one caused by the actual westward traveling surge. Judging from the combined all-sky television data, however, it is concluded that both cases exist and that at times pulsating arcs form immediately prior to breakup of the poleward discrete arc in the evening and early midnight sectors. This behavior is probably a growth phase phenomenon.

Due to the low density of pulsating forms, the low intensity and the slow pulsations, these auroral arcs and arc segments are not readily observed by any technique applied in earlier observations.

4.6 Streaming Pulsation

Streaming differs from stable pulsations by showing a time-dependent spatial variation. The visual impression is of a form expanding and retracting in a horizontal direction as it increases and decreases in intensity. Whereas stable pulsating aurora appears only to represent variations in the particle flux within a magnetic flux tube of fixed shape, streaming as used here implies a variation in flux within a magnetic flux tube that is changing its area as the pulsating occurs. Alternately, it can be thought of as variation within a fixed flux tube wherein the intensity increases first at one point or region that expands laterally to equal the entire flux tube as time progresses. Cresswell (1968) used the term streaming when he described observations of this phenomena in his report on pulsating aurora, but until the all-sky TV was applied to auroral observation, the extensiveness of the streaming phenomenon was not recognized.

Figure 4.6 shows an example of a streaming patch that is drifting west. The pulsation in this example is comparatively slow but in no way unusual. This particular example is chosen because the streaming expansion is slow enough to permit illustrative photographs. The modulation during this sequence is less than 100%; at other times, however, the same patch appeared to have a modulation of 100%. The outline of the maximum extent of the patch is visible throughout the whole sequence. The core of the patch is located north of the zenith, and the streaming is in the southeast direction. Note that the boundary facing the other pulsating form to the southwest is much sharper than the boundary around the rest of the streaming patch. This is typical where two patches are located close together.

Figure 4.7 shows another more complex form of streaming pulsation in which the streaming direction changes during the expansive phase of a pulsation. The patch to the far right in the picture first streams to the south for two seconds, then the streaming direction changes to southwest for another second or two. As this part of the form reached its maximum extent, another portion started to stream out to the southwest. The whole growth phase lasted for five to six seconds. This example was also chosen because its relatively slow streaming allows easy illustration.

The patches in both Figs. 4.6 and 4.7 are larger than usual (>100 km); the more typical patches of somewhat smaller size exhibit faster temporal behavior. Still, these examples illustrate the time-dependent spatial variation that characterizes streaming pulsations. Streaming pulsations occur in both eastward and westward drifting forms. The shape, size, intensity, modulation amplitude and frequency of these forms are no different than that given in the descriptions of eastward and westward drifting patches, above.

In most cases both the growth phase and the decay phase of a pulsating auroral form show streaming. However, the decay phase is not always the exact reverse of the growth phase. At times only the growth phase shows streaming, and then the intensity decreases uniformly over the active part of the form leaving only a core of light during the off period. Streaming also occurs in arcs where it appears in two different ways. Most commonly, the arc is visible before the pulse starts, and a region of enhanced luminosity travels along the arc in the east-west direction. The region of enhanced luminosity may either be of constant size and travel in one direction along the arc, or it may spread out along the arc in one or both directions. The velocity of this kind of streaming is usually high and it has, on some occasions, been observed to move across the entire field of view in one or two seconds. This movement corresponds to a velocity of several hundred kilometers per second. The other type of streaming in arcs is perpendicular to the pulsating arc. The whole east-west aligned arc moves north-south as it pulsates on and off. Unlike most streaming pulsations, it is not the size of the structure that changes, but its location. The displacement in the north-south direction is usually small, roughly equal to the width of the arc itself.

4.7 Split-Streaming

Another type of streaming pulsation is here called split-streaming. As the name implies, the streaming patches and arcs exhibiting this behavior split up into two or more separate forms as the spatial extent increases. The pulsation growth begins within a streaming patch or arc. By the time the patch or arc has reached its maximum extent, it splits up into two patches or arcs of approximately the same size. The primary patch or arc, the part covering the area where the pulsation first appeared, is usually stable and not drifting. The secondary patch or arc may or may not drift away from the primary one. If drift occurs, it is always in the direction of original streaming away from the primary structure.

Decrease of intensity usually occurs in the secondary patch or arc before, or at least at the same time, as it takes place in the primary patch or arc. The decay of the primary patch follows the same pattern as simple streaming pulsation. Quite often the primary patch or arc has a minimum intensity different from zero while the secondary patch almost always disappears.

To complicate the picture even further, both the primary and the secondary patches have been observed to disappear and, during the next sequence, the primary patch has appeared at the location where the secondary patch from the previous sequence disappeared. The sequence of streaming and splitting in this case reverses from one pulsation to the next to give the appearance of 180° change in streaming direction.

Split-streaming pulsation occurs within most pulsating displays in the midnight sector coincident with simple streaming pulsation. Split-streaming is seldom seen in the morning sector and not at all in the evening.

Although the impression is that this kind of pulsation occurs most often in patches, it is not uncommon in arc segments and arcs. Depending on the distance of streaming, the velocity and direction of the streaming, and the time between sequences, the behavior more-or-less resembles what Cresswell (1968) defined as fast auroral waves. However, it is equally clear that split-streaming incorporates a wider variety of phenomena, so that Cresswell's fast auroral waves represent a sub-class of split-streaming wherein the streaming distance is relatively large.

Another indication that Cresswell's fast auroral waves are a type of streaming appears in his thesis where he says, "In none of the cases did discrete, large, eastward drifting patches occur over Alaska, either in the time between substorm onset and wave display, or during the display. In one case their appearance signaled the end of a wave display." This statement indicates that fast auroral waves occur in the midnight sector where the different forms of streaming are most common. Furthermore, the all-sky TV observations are fully capable of detecting the phenomenon Cresswell called fast auroral waves, so it is obvious that the data studied here include examples. Yet the analysis alone suggests that the fast auroral waves are a sub-class of streaming rather than a separate phenomenon.

Consequently, it appears that pulsating aurora is composed of a continuum of types ranging from stable, fixed-area pulsating forms through the more complex streaming and split-streaming forms to the rapidly streaming variations referred to by Cresswell as fast auroral waves.

4.8 High-Frequency Modulations

Although low-frequency (<1 Hz) pulsations are seldom very regular, each pulse may be modulated by a high-frequency variation. Within the uncertainty of the data these modulations maintain a steady frequency throughout the whole pulse. Generally, the frequency is the same in all modulated patches in the display, but it may change slightly as the display changes. Examples of the high-frequency modulation of lower-frequency pulsations are given in Figs. 4.8 and 4.9. Figure 4.8 shows semi-periodic pulsations with a 4-5 sec period. The high-frequency modulation is relatively low, and the amplitude varies somewhat from one pulse to another. Notice that the high-frequency modulation is also recognizable between pulsations at times when the minimum intensity is different from zero.

Figure 4.9 shows one of the better examples of high-frequency modulation. The intensity trace in Fig. 4.9A shows the evolution of a pulsating event in small patches with approximately 2 sec period and no modulation, through moderate modulation and irregular pulsations with almost 100% high-frequency modulation. The modulation frequency in this case is very stable at 3 Hz. Whereas the tracings in Figs. 4.8 and 4.9A represent the intensity variation in a small region of size, Fig. 4.9B shows tracings obtained with a photocell covering the entire TV screen. Figure 4.9B illustrates the problem involved in interpreting the integrated light from a great number of patches pulsating out of phase. The high-frequency modulation is much smller relative to the total light intensity. Furthermore, some of the low-frequency pulsations are caused by patches not modulated by a high frequency.

Whereas the high-frequency modulation shown in parts of Fig. 4.9A is between 50% and 100%, a more usual modulation is 20% or less. In Fig. 4.9A the amplitude of the high-frequency modulation is relatively constant with time.

At times when no high-frequency modulation is visible in the all-sky data, it may be very pronounced in the concurrent narrow-field data. In fact, all but a few of the pulsations observed in the narrow-field records showed some degree of high-frequency modulation. An example is shown in Fig. 4.10 where simultaneous intensity recordings from the narrow-field and the all-sky TV cameras are presented. The analysis window was the same for both recordings to keep it as close to visual impressions as possible. Consequently, the area at auroral altitude represented by the lower trace in Part C is much larger than represented by the upper trace. High-frequency modulation is seen in the upper trace whereas none is seen in the lower. The pictures (Parts A and B) show the display in the all-sky and narrow-field cameras. The display at the time shown consisted of diffuse arcs superimposed on a diffuse background with little or no large- or small-scale structure. Many other examples exist wherein pulsating patches show high-frequency modulations in the narrow-field data while none are recognized in the all-sky data.

It appears that high-frequency modulation is a very common phenomenon associated with pulsating aurora and in fact, study of the narrow-field TV data suggests that high-frequency modulation is present in most forms of pulsating aurora.

High-frequency modulation is most easily recognized in diffuse, uniform, large patches or arcs that are modulated uniformly over the whole form. However, more common is the auroral form wherein the high-frequency modulation is not of uniform intensity over the whole structure. In fact, in many cases, the main part of the form is stable and only part of its boundary shows high-frequency modulation.

Although diffuse pulsating patches with no internal structure are the most common, there is a substantial percentage of pulsating patches with internal structure. At times this internal structure is so weak or small that it is observed only in the narrow-field TV data. Each form is divided up into multiple regions with more-or-less parallel boundaries, and each of these regions are high-frequency modulated independent of any other regions in the form. Consequently, no high-frequency modulation will be observed in the wide field of view if the internal structure is below the limit of resolution. When two adjacent regions are modulated approximately 180^0 out of phase and with the same high frequency, the visual impression will be of a region oscillating in space.

The same type of alternating fast modulation has also been observed in a portion of a display consisting of several thin east-west arc elements bounded on the north and south by rayed arcs. Not only did the high-frequency modulation within these thin arcs change from one arc to another, the whole group of arc elements showed a semi-periodic spatial oscillation in the north-south direction. High-frequency modulation may not be present in all the regions at all times. It has been observed that high-frequency modulation may oscillate between two adjacent regions and last for a few seconds in each. By comparison, the low-frequency variations of period 2 sec or more, are typically uniform over the entire patch.

High-frequency modulation is observed in patches with edges and internal structure both well-defined or diffuse. Examples illustrating the high-frequency modulation in pulsating aurora with considerable fine structure are shown in Fig. 4.11. In these examples, the highest modulation occurs when the intensity is at maximum. Both tracings were made from narrow-field TV data, but in these cases similar results were obtained from concurrent all-sky TV records, i.e., integration over a larger area.

The slow pulsations in Fig. 4.11A also provides an example of the danger of describing pulsations from intensity traces. It is seen by inspection of the television screen that the intensity variations are made up of two very distinct features. One is the regular on-off pulsation of a patch. The other is the spatial movement of patches in and out of the field of view of the analysis window. There is no real way of telling these two effects apart by looking at the trace. The same problem exists in data obtained with a photometer. By looking at the narrow-field TV screen, however, one gets the impression, in this particular case, that the spatial variation contributes substantially to the appearance of the tracing. The all-sky data give a similar impression.

Figure 4.11B shows an example of low-amplitude pulsations on a diffuse background. Here the amplitude of the high-frequency modulation varies, but the overall background level remains relatively constant.

4.9 Dual Layer Pulsation

The term dual layer pulsation is used to refer to a display with two apparently overlapping groups of aurora, of which at least one is of pulsating nature. Indications are that these two different groups of aurora are caused by particles of different energy, hence the name, dual layer. A typical dual layer pulsating display consists of diffuse patches or broad east-west-aligned arc segments superimposed on a background. The forms are usually stable but may show streaming and even high-frequency modulation. From all the data studied, no indication has been found that these pulsations are different from other pulsating patches and arcs. The pulsations in these forms are generally slow, with periods in the range 5 to 20 sec. If the background is not included, the pulsating amplitude is close to 100% in most cases. In those cases where it is considerably less than 100%, the background is not observable behind the forms. However, in the space between individual forms the background is always visible, so no difficulty exists in identifying such a display. The patches and arc segments are large and of an order of magnitude greater than the structures in the background, if any.

In some cases the background, as well as the distinct forms, also pulsates. The simplest type of background is one that is uniform throughout the whole field of view or over at least a large portion of it, and with a fairly sharp east-west boundary on the south side. Measurements of the absolute intensity of the background are not available; but at times the layer is so intense that only a few of the brightest stars are visible through it, implying an intensity of several kR in 4278 Å.

Figure 4.12 shows a series of pictures of a display with dual layer pulsations and tracings of intensity variations in Parts J and K. Parts A and B show the display as seen by the all-sky TV camera. Note the difference in the two pictures that illustrates the behavior of the pulsating patches. Figure 4.12, A and B, also show a typical poleward boundary consisting of one or more non-pulsating arcs. In this example even some discrete aurora can be seen near the northern horizon. Figure 4.12C through I are from the narrow-field TV camera pointed at the magnetic zenith. These photographs were taken when the pulsating patch was alternating at minimum and maximum intensity. During maximum intensity little or none of the background structure can be seen. Note that the pulsating form is much greater than the field of view while the weak structures within the background are smaller than the field of view. The background in this example consists of east-west-aligned arc segments that are drifting to the east. The intensity tracing presented in

Fig. 4.12J shows the variation during the time the pictures were taken. Between 12:57:20 and 12:57:45 there were no pulsations inside the narrow field of view, and the variations seen in the trace are due to changes in the background. The tracing in Fig. 4.12K is from the same spot 70 sec later; it shows, at this time, that the pulsations had a high-frequency modulation.

The drift in the background portion of dual layer pulsations is always to the east with a speed that appears to increase with closeness to the poleward boundary of the pulsating aurora. The fact that the background is drifting and partly obscured by a pulsating patch makes it difficult to study systematic changes. There are indications, however, that some of the structures in the background may be pulsating with a much lower frequency than the main patches or arcs. These pulsations have been observed in only a few cases and are not a dominant feature in the background. It is not feasible to make an intensity recording of these pulsations in the background because the high drift velocity combined with the small size and low frequency prevents the structure from remaining inside any reasonable analysis window long enough to undergo one pulsation. Also, the much stronger and faster pulsations of the larger forms often totally obliterates any pulsations in the background. It is possible that the background is caused by softer particles than the pulsations and, as a result, the two auroral portions of a dual layer display are located at different altitudes with the pulsating forms being below the background, a point to be discussed more fully later.

4.10 Black Aurora

Black aurora (Nazarchuck, 1975) is a phenomenon not contained within the classification of pulsating aurora, but it occurs in association with pulsating aurora. Virtually no information on black auroras is contained in the literature, and what is believed to be new insight into this phenomenon is presented here.

Black aurora is defined as a small region of very low-light intensity embedded in a bright uniform background. Black aurora appear to be forbidden regions in the aurora. They are frequently observed in all-sky and narrow-field TV data taken from College.

Black aurora was observed within a diffuse background covering the whole field of view of the all-sky TV on March 21, 1973. Several narrow east-west arcs were superimposed on the diffuse background at 10:30 (see Fig. 4.13). At this time, several small black spots started to form. The spots formed one at a time, and were approximately 1 to 2 km in north-south and 4 to 10 km in east-west dimensions. They formed north of weak east-west arcs embedded in a diffuse background of auroral emissions. As more of the spots formed, it became obvious that they were aligned in several rows. They all drifted east with a velocity of approximately 3 km/sec.

At approximately 10:32, a small loop in the brightest arc to the south moved through the field of view from east to west, shifting the arc some 20-30 km to the north. As the arc moved north, so did the black auroral spots so as to form several rows with the same shape as, and parallel to, the arc, as illustrated in Fig. 4.13. After the arc had moved north, the black regions started to inter-connect to form east-west aligned black bands extending across the field of view. At this stage, it became a matter of opinion as to whether they were black arcs on a bright background or bright arcs on a dark background.

The result of this development was that a region of diffuse, relatively uniform background changed into a region with closely-spaced parallel arcs superposed on a dark background to the north and a diffuse brighter background having east-west-aligned arcs superimposed on it. It is common to observe such east-west-aligned arcs on a bright background during the recovery phase of a substorm, and these occasionally pulsate.

Another observation of black aurora was made on February 7, 1975 near 12:51. In this case (Fig. 4.14, A and B) the background upon which the black aurora formed was diffuse and homogeneous. However, just to the south there was a band of relatively bright arcs in a dark background. That background, being much darker than the background existing over a broad region, might itself be called black aurora. The thin arcs were pulsating rapidly; their original formation was not observed so it is not known how they developed initially. The row of black spots shown in Fig. 4.14A formed near 12:51:04, all spots within the row appearing simultaneously. The spots lasted only 3 or 4 sec. Ten seconds later a dark band, or arc segment appeared at a location a few kilometers to the south of the location of the first array. This arc segment immediately developed into the array of black curls shown in Fig. 4.14B. It also lasted only a few seconds. Both arrays of black spots drifted eastwards at 200 to 300 m/sec during their lifetimes.

The spot array in Fig. 4.14B is particularly interesting because it clearly is in the form of an inter-connected array of black vortex structures showing clockwise rotation as seen viewing antiparallel to $\vec{B}$. Whereas the overall black spot array was drifting to the east, individual vortexes propagated westward.

Approximately 2 min after the appearance of the black spot arrays shown in Fig. 4.14, A and B, the narrow-field TV was recording a structureless diffuse background in the zenithal region. Across the region there drifted a thin black void shaped like an arc element, as shown in Figs. 4.14, C, D, E and F. As the black arc elements drifted eastward, there was indication of growth of irregularities along its two boundaries but the growth quickly damped out. Still, there was enough irregularity to recognize that the irregularity structure was drifting westward.

In various ways, the black aurora is analagous to a negative of normal aurora. The name "black aurora" has been applied to the phenomenon independently by observers on different continents. According to T. N. Davis (private communication), observers at College, Alaska used the name for many years, partly in a jocular sense, without realizing that the black aurora is something more than an artifact of visual observation.

4.11 Omega Bands

Omega bands are described in the literature, most recently by Akasofu (1975). During the morning hours when a broad region of pulsating aurora appears overhead at the latitude of College, it is common to observe bright, rayed irregular bands well to the north and completely detached from the weaker, relatively diffuse, pulsating region overhead. In addition, there sometimes appears at the north edge of the diffuse region, a bright, convoluted band of rayed aurora called the omega band because of its shape, similar to the Greek letter omega (Ω). The top of the letter is toward the diffuse region where it forms a boundary to this region.

An example of an omega band is shown in Fig. 4.15; at the time of its appearance on March 14, 1975, both narrow-field and all-sky TV cameras were operating. Just prior to the appearance of the omega band there existed a typical display of eastward drifting, dual layer, diffuse pulsating arc segments. Arcs near the poleward edge of the region were substantially brighter than those further south. All arc segments were pulsating, and none showed ray structure at this point; see Fig. 4.15A. The omega band structure drifted from the west into the field of view of the all-sky television (Fig. 4.15B). As the omega band drifted into the field of view the poleward arc changed from diffuse pulsating to a distinct rayed arc. By 13:01:00, Fig. 4.15C, the omega band was within the field of view of the narrow-field TV, pointed at the magnetic zenith. That camera recorded an interesting sequence. First there were diffuse dual layer pulsations wherein the background was aligned east-west. Then the pulsations stopped and the background became aligned parallel to the omega band. When the omega band itself came into the field of view, a sharp spatial transition was seen between the diffuse background just described and the bright, rayed omega band containing pronounced, fast-moving curl structures. At the north boundary, flickering (Beach et al., 1968) was observed. Continued eastward drift of the overall structure caused this spatial sequence to be observed again during the overhead passage of the trailing portion of the omega band, providing verification that the overall sequence described above was spatial and not a temporal variation. The example shown in Fig. 4.15 is typical of omega bands observed at College. Whereas the omega bands occur contemporary with pulsating aurora, they form poleward boundaries to the pulsating region and they exhibit quite different characteristics. These characteristics are, in fact, more akin to those observed in breakup aurora seen in the midnight and late evening sectors during the expansive phase of the magnetospheric substorm. Several other examples of Ω-bands in the all-sky television data justify the following conclusions. Omega bands are always located at the poleward boundary of the diffuse morning auroral oval, where they develop from a previously pulsating arc. Observed eastward drift velocity is always higher than the drift velocity of eastward drifting patches. Omega bands always show a rayed arc structure with occasional flickering.

4.12 TV observation of Pulsating Aurora and Corresponding DMSP Photos

The availability of topside scanner images obtained by the DMSP satellites permits examination of the large-scale characteristics of pulsating aurora and of the relationship between pulsating aurora and other parts of the auroral display. From the DMSP images alone one cannot tell if a particular region of aurora is pulsating or not. But simultaneous television or all-sky camera and DMSP observations do permit the accrual of enough information about the appearance of pulsating aurora in DMSP images to use the extensive DMSP collection as a major tool for determining global aspects of pulsating aurora. As yet, there are available only limited simultaneous observations. Among the numerous DMSP satellite passes over the College, Alaska area, only four resulted in simultaneous satellite and TV observations of the aurora. In the following data, Fairbanks/Eielson is either visible in the field of view, or obscured by a bright part of the auroral display. Only all-sky television data are used in this section.

4.12.1 Satellite Passes 2740-41, February 26, 1974, 10:26 and 12:07

On February 26, 1974, DMSP satellite 7529 acquired two passes of interest, crossing over or near Alaska at 10:26 and again at 12:07. Prior to the first pass there was a minor substorm at 8:13. Later arcs reformed to the north and outside the field of view of the College all-sky television. At 9:49 a quiet homogeneous arc had drifted into the field of view from the north. As the arc drifted south it became evident that there was a broad diffuse region to the south of the arc. A new breakup started at 9:59 and lasted until 10:07 by which time a westward-traveling surge had passed over College. After that, some rays appearing within a diffuse background had formed and died away again. In this region the first pulsations started around 10:12, and, at

12:22, the display consisted of streaming pulsations with some split-streaming and fast auroral waves (a sub-class of streaming) propagating to the south. At 10:26, the time the satellite made its first pass to the northwest of the station, the all-sky TV showed fast auroral waves (Figs. 4.10, A and B). At 10:28, the display exhibited both simple streaming and fast auroral waves.

The DMSP image contained in Fig. 4.16C shows a large spiral to the west of College. College is located just inside the right hand edge of the picture. The auroral display east of the spiral consisted of a region of diffuse east-west-aligned arcs and arc segments. This was a broad region, several hundred kilometers in north-south extent. (Both streaming and fast auroral waves are at times found in the envelope of arc segments and patches that is often observed to appear just after a westward traveling surge as it propagates along the arc to the west in the evening sector; see also Fig. 5.1 containing a DMSP pass at 14:45 on January 25, 1973). The tracings in Fig. 4.16D indicate the pulsating behavior overhead College; they show relatively short-period pulsations with a maximum intensity that varies with time.

Around 10:35 the pulsations died away, and very little aurora was left in the field of view. By 10:55

when pulsations again started, the display was more stable and consisted of streaming patches without fast auroral waves. The number of pulsating patches was large and the frequency of pulsation was high when the pulsations commenced. During the next hour both the numbers of pulsating forms and the frequency decreased. By the time of the next satellite pass (12:07) a broad band of diffuse aurora had formed, within which several east-west aligned arcs pulsated slowly. Figures 4.17, A-F show the appearance of the display during the satellite pass.

In the DMSP picture shown in Fig. 4.17, it appears that the spiral of Fig. 4.16 has turned into a large loop. The intensity to the east has decreased and the display consists of a broad region with diffuse, somewhat east-west aligned arcs. Again, College was located inside the picture to the east. Examination of the College magnetic record during the period of interest and other observations indicate that the aurora observed after 12:00 was typical of late recovery phase of the substorm. The slow infrequent pulsations shown in Fig. 4.17H are typical of this phase of the substorm.

4.12.2 Satellite Passes 9874-2650, 12:15 and 12:37 February 20, 1974

The auroral display of February 20, 1974, started at College with the appearance of a quiet diffuse arc in the north. Later, a breakup occurred at 11:50. By 12:05 the expansive phase was over, and recovery had begun. Then at 12:07 small patches began pulsating slowly with period 4-8 seconds. These patches are shown in Figs. 4.18, A,B, and C near 12:15, the time when DMSP satellite No. 7529 passed over Alaska. Active rays visible on the northern horizon evidently were located in the northern edge of the display observed in the scanner image, Fig. 4.18D. As shown in Fig. 4.18E, slow, stable pulsations of period 1-15 sec continued for some minutes. Throughout this display the aurora drifted toward the east. Figure 4.18D shows that a series of small spirals formed the northern boundary of the aurora. South of the convoluted structure, there is a diffuse region to the east with patches extending out of the field of view. This is the portion of the display photographed from below in Figs. 4.18, A, B, and C. Approximately 20 min after the overhead passage of DMSP satellite No. 7529, satellite No. 5528 also passed over Alaska. Figures 4.19, A, B, and C contain reproductions of the all-sky TV images obtained during the passage of the satellite. These images show a more diffuse background than had existed previously. At this time the patches show a northeast to southwest alignment, a characteristic also seen in the scanner image, Fig. 4.19D. The temporal behavior of the pulsations is shown in Fig. 4.19E. Such behavior involving slow, low-amplitude pulsations in a broad diffuse band of eastward drifting patches is typical in the morning sector during the recovery phase of a small substorm. That the portion of the display described in this example occurred during the recovery from a small substorm is indicated by examination of the College magnetogram.

4.12.3 Satellite Pass 2540, 7:57 December 12, 1973

The display of December 12, 1973, at College started out in typical fashion with the appearance of a quiet arc to the north of the station. At 07:22 a westward traveling surge, or spiral, passed overhead leaving only diffuse non-pulsating westward drifting patches overhead. By 07:33 the patches had formed into diffuse east-west-aligned arcs which pulsated very weakly. The pulsations continued until the time when DMSP satellite No. 7529 passed overhead at 07:57. A bright arc in the north was just inside the field of view of the all-sky TV.

The intensity recording (Fig. 4.20) shows that each pulse lasted from three to four seconds with time between pulses of from 20 to 60 seconds.

On the DMSP photographs, College is located in a band of weak diffuse auroral arcs located south of a fairly strong east-west-aligned arc. A large spiral-like surge is seen over the Canadian arctic in the DMSP image. Undoubtedly it is the surge that passed overhead College at 08:05. Hence this sequence is an example showing that pulsating aurora can occur in the evening sector prior to a westward-traveling surge.

4.12.4 Satellite Pass 2725, 09:04 February 25, 1974

The display of February 25, 1974 started with the usual evening arc to the north of College. This arc moved slowly northward beyond the horizon leaving weak arc segments over the whole field of view of the all-sky TV. At 08:10, these segments began pulsating very slowly. The College magnetogram shows that a substorm started just before 08:00 and that its recovery continued until 09:00. A surge passed College to the north, outside the field of view of the camera. Pulsations continued more-or-less continuously until 09:04, the time of the passage of Satellite No. 7529.

At this time a stable arc could be seen inside the north edge of the field of the all-sky TV. Arc segments to the south were very weak but appeared to have a high-intensity variation. The recording of this intensity variation, Fig. 4.21, shows that the display was pulsating continuously and with pulses lasting from 2 to 5 seconds. On the DMSP picture there is a hint of some very faint aurora south of the bright arc. Unfortunately, the reflection in the light shield covers the Fairbanks area, so the topside view of the aurora directly over College is missing.

Here again is an example of pulsating arcs and arc segments in the early evening sector in the recovery phase of an auroral substorm. These arcs or arc segments lie to the south of realigned discrete auroral arcs and are somewhat weaker.

4.12.5 Satellite Pass 899, 16:31 January 11, 1973

One of the better examples of a scanner image of the auroral oval is from Pass 899, 16:31, January 11, 1973 (Fig. 4.22A). At this time, College was located in the late morning sector. No simultaneous television observations are available, but excellent 16 mm all-sky data, Fig. 4.22B, showed patches undergoing intense pulsations. The low rate of photograph acquisition precluded measurement of the frequency of the pulsations.

In Fig. 4.22A, diffuse auroral arcs to the north of the pulsating patches are visible. Also visible, in Fig. 4.22A, are a bright westward traveling surge in the evening sector and a region of bright and diffuse patches in the midnight sector. The AE index, lower portion of Fig. 4.22A, indicates that the display is from the early recovery phase of a moderately intense substorm.

To be certain that the fluctuations in the all-sky film of the type shown in Fig. 4.22B are actually caused by pulsations, all-sky film and television recordings were compared for times when such simultaneous data were available. The result was that pulsations on the all-sky film always corresponded to pulsations in the television data, but it was not always possible to identify pulsations on the television with intensity fluctuations on the all-sky film. The obvious reason for this is that a display has to be fairly stable and must pulsate for several minutes to give a beat frequency in a data set sampled only once a minute.

CHAPTER 5

INTERPRETATION: DEVELOPMENT OF A GLOBAL MODEL OF PULSATING AURORA

5.0 Introduction

Here the intent is to bring together and interpret the various observations presented in Chapter 4 in order to develop a cohesive description of pulsating aurora. Where appropriate, results obtained by others are brought in to help formulate a unified description of both small-scale and large-scale aspects of the phenomenon. In particular, the auroral substorm model of Akasofu (1968) is of special value because the description of pulsating aurora to be given here is couched in the framework of that model and represents an extension of it.

5.1 The Auroral Substorm

According to Akasofu (1968), an auroral substorm starts with a southward motion and a sudden brightening of the quiet arc or arcs of discrete aurora that constitute the discrete auroral oval at quiet times. Shortly after this initial brightening, a bulge will form in the midnight sector expanding first in all directions, disrupting the quiet arcs and leaving rayed arc segments in the wake behind.

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To be certain that the fluctuations in the all-sky film of the type shown in Fig. 4.22B are actually caused by pulsations, all-sky film and television recordings were compared for times when such simultaneous data were available. The result was that pulsations on the all-sky film always corresponded to pulsations in the television data, but it was not always possible to identify pulsations on the television with intensity fluctuations on the all-sky film. The obvious reason for this is that a display has to be fairly stable and must pulsate for several minutes to give a beat frequency in a data set sampled only once a minute.

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As the expansive phase of the substorm continues, the expanding bulge will form into a rapidly westward traveling spiral and a less spectacular surge traveling to the east. As the westward traveling spiral or surge moves west, it breaks up both the east-west aligned discrete arcs and the diffuse aurora that usually is located to the south of the discrete arcs (Fig. 5.1). The surge starts out as a large spiral of rays and rayed arc segments. Both the arc segments and the individual rays exhibit complicated and fast motions. As the surge reaches the early evening sector, it takes the shape of a folded arc as shown in Fig. 5.1. The expansive phase of a substorm is rather short, about 15 to 30 min. In the wake of the westward travelling surge, diffuse patches and arc segments form. These patches and arc segments often show different kinds of pulsations. In the recovery phase, which typically lasts from 1 to 2 hours, the activity will decrease and the different forms in both the diffuse and discrete aurora will realign into arcs.

Akasofu (1964) presented a schematic diagram showing the development of the auroral substorm; a similar diagram with emphasis on the location and the form of the pulsating aurora is presented in Fig. 5.2. In connection with this figure, a table (Table 5.1) was made to show the combinations of different geometrical forms and different temporal variations. Figure 5.2 and Table 5.1 serves as a reference for the following description of the global model of pulsating aurora.

5.2 Pulsating Display in the Evening Sector

An auroral display in the evening sector will, before the start of a substorm, exhibit a stable discrete arc poleward of a diffuse region of uniform luminosity. Pulsating arcs have been observed immediately prior to breakup in the evening and early midnight sector. The data, however, are not conclusive on this point, but some examples indicate that pulsations start in the evening sector at the time or immediately before breakup occurs in the midnight sector and lasts until the arrival of the much more intense westward traveling surge. Such a display of pulsating arcs in the evening sector will not last very long, 15 to 20 min at most, before it is disrupted by the westward traveling surge breaking up both the stable discrete arc to the north and the pulsating arcs superimposed on the diffuse auroral region equatorwards into pulsating patches. After the

TABLE 5.1

Occurrence of Pulsating Aurora in the Auroral Oval

			East of westward traveling surge			
	Quiet times	Arcs in early substorm west of westward traveling surge	Patches and arc segments in the midnight sector in early recovery phase	Patches in the morning sector in the early recovery phase	Arcs in the midnight and morning sectors in the late recovery phase	Arcs in the evening sector in the late recovery phase
Stable pulsations	Never	Uncommon	Uncommon	Common	Common	Common
Streaming, east-west*	Never	Uncommon	Never	Never	Common	Common
Streaming, any direction	Never	Never	Common	Uncommon	Uncommon	Never
Split-Streaming and F.A.W.	Never	Never	Common	Never	Uncommon	Never
High frequency modulations	Never	Never	Common	Common	Common	Never

*Only in arcs and arc segments

passage of the westward traveling loop in the evening sector, the remnants of the arcs will start realigning first into arc segments and then into arcs, all the while pulsating. Pulsating forms in the evening sector in the recovery phase of a substorm are more active than those in the initial phase of a substorm, but still quiet compared to pulsating forms in the midnight and morning sector.

At times a second substorm may follow before the arcs have recovered completely. A situation will result in which recovering pulsating arcs and arc segments from the first substorm are disrupted by the arrival of the westward traveling surge of the second substorm. There are, however, differences between these two types of pulsating arcs in the evening sector. Those early in a substorm are always perfectly aligned along the east-west direction and parallel to each other, while those in the late recovery phase are not always straight arcs, as when not completely recovered after a substorm.

5.3 The Westward Traveling Surge

After the front of the surge has passed over the observing station, the display becomes less intense. The fast-moving rays and curls disappear leaving weak uniform patches in its wake. This transition of the display from arcs to pulsating patches usually takes 10-15 min, but on rare occasions such a transition may take less than a minute for the rayed arc to form into pulsating patches. During such a fast transition the front of the surge will still be visible in the field of view when the pulsations start overhead. It is sometimes possible to observe the individual form as it changes from a rayed arc segment to a weaker diffuse patch containing little or no internal structure. This patch will immediately start pulsating.

At other times the surge may take 10-15 min to pass over a station and disappear beyond the western horizon leaving nothing but a dark sky with no visible auroral forms (see Fig. 5.3). Later, pulsating patches will form and drift westward. Note the dark sector behind the westward traveling surge in the DMSP picture (Fig. 5.3). From what has been said before, it may be concluded that the region east of this dark sector shows pulsations, while the one to the west does not.

5.4 Pulsating Display in the Midnight Sector

The most complex part of the pulsating auroral display is the midnight sector during a substorm (Fig. 5.3). In the midnight sector, there is a broad irregular diffuse region containing numerous patches and irregular arc segments with complicated fine structure described in detail in Section 4.3.

The equatorward boundary of this midnight region is diffuse with intensity decreasing gradually to the south and with no sharp or distinct large-scale forms. This boundary is very even in the east-west direction lining up with the equatorward boundary of the evening and morning sector to form an almost perfect arc. This equatorward boundary constitutes a sharp contrast to the poleward boundary of the diffuse auroral oval in the midnight sector which is very irregular and changes position and shape during the substorm. Pulsating patches on a diffuse background form the equatorward half of the diffuse auroral oval in the midnight sector until late in the recovery phase of the substorm. Late in the recovery phase, however, they may, at times, align into arc segments showing a strong streaming pulsation that tends to develop into split-streaming and fast auroral waves usually streaming from north to south.

In contrast to the equatorward half of the midnight sector which does not show any large-scale structure, the poleward half almost always shows some large-scale structures. The most common is the formation of torch-like structures (Akasofu, 1974; Montbriand, 1969) as shown in Figs. 5.3 and 5.4.

Torch-like structures are regions of high luminosity extending north at the poleward boundary of the diffuse aurora. Torches occur in groups of 3 to 10 and each torch shows a core of pulsating patches and with north-south-aligned arc segments along the boundaries to the east and west. Both the DMSP photos and the all-sky TV data, show some auroral forms in the dark regions between the torch-like structures. The arc segments located in the dark region, like those in the torches, are aligned mainly north-south, and are usually pulsating. Figure 5.4 shows an example of a torch-like structure as seen by the all-sky TV from the ground. There is so far no set of corresponding DMSP photos and television recordings of this phenomena, but Akasofu (1974) has presented several examples of DMSP photos and corresponding all-sky camera pictures showing torch-like structures in both sets of data.

Streaming from the center of the torch-like structure towards the edges occurs and is generally observed in the north-south-aligned arcs that form the boundary of the torches. This streaming is usually most intense closest to the boundary. All-sky TV data show that in many cases, the trailing boundary of a torch has been much more well-defined than the leading boundary. This observation has, to a certain extent, been supported by DMSP photos. There are also indications that the pulsations are strongest on the trailing edge.

The central core of the torches consists mainly of stable patches and the overall intensity is usually higher in this part of the torch than at the boundaries. These patches do not differ from those in the more homogeneous region to the south.

Drift from east to west has been present in all examples of torches observed with the all-sky television. Measured drift velocities corresponded to the velocity generally measured in westward drifting patches and arc segments, 300-900 m/s. Apart from the streaming of the boundary, the whole torch-like structure drifts west as a unit. Figure 5.4, A, B and C shows an example of the trailing edge of a torch drifting west while the north-south arc segments are streaming to the east. This can be seen in pictures B and C where C is later in time than B. However, in C an additional streaming arc segment is visible whereas it is not seen in B.

Torch-like structures, when they have been identified as such, have always been composed of pulsating patches in an envelope of pulsating and streaming arc segments. Akasofu (1974), suggested that torch-like structures might be closely related to omega bands. However, while torches are drifting to the west, omega bands are always propagating to the east. And while torches are showing a structure of pulsating patches and arcs, omega bands show fast moving curls, rays, and even flickering.

Most DMSP photos show that an auroral display exhibits torches in the poleward diffuse aurora when the discrete aurora is separated from and located poleward of the diffuse aurora.

High-frequency modulation has been observed both in the patches and in the north-south-aligned streaming arc segments in the torch-like structures.

From the available all-sky TV data, it is not possible to determine the development of these torches because of their large size and motion prevents them from staying in the field of view for a time comparable to their development time. However, the DMSP photos suggest that they form on the border between the midnight and morning sector and then drift westward while maintaining their size, or even decreasing in size as they drift closer to the remnants of the westward traveling surge in the evening sector.

Akasofu (1974) distinguishes between filamentary and brush-like torches, the former being somewhat filamentary at the poleward boundary while the latter is rather uniformly bright. Such a difference is not obvious in the all-sky television data. However, some torches have been observed in the DMSP images to have a smooth curved boundary of arcs to the north, while others have a poleward boundary of short arc segments aligned north-south. An example of the former is shown in Fig. 5.3, while Fig. 5.1 shows the latter.

In a display where the discrete aurora is located closer to the diffuse aurora in the midnight sector, the torch-like structures disappear and the discrete auroral arcs break up into rayed arc segments. Such a display forms a more even northern boundary of the auroral display in the midnight sector with discrete non-pulsating rayed arc segments and pulsating patches mixed (see Fig. 5.5).

In this boundary region of pulsating patches and rayed arc segments, pulsating patches may stop pulsating and brighten up. They will start forming a ray structure when the intensity reaches a sufficiently high level. After a few minutes with active ray structures, the intensity will again decrease and the form will once more turn into a diffuse pulsating patch. This transition is very similar to the one occasionally observed in a westward traveling surge where rayed arcs and arc segments transform into pulsating patches in a short period of time. The difference seems to be that, in the latter case, the transition is from pulsating patches to rayed arcs and back to patches while in the former, it is only from rayed arcs to pulsating patches.

As the substorm recovers, both the discrete aurora to the north and the diffuse pulsating aurora to the south in the midnight sector will start to realign into east-west-aligned arcs. Usually this effect starts in the north and spreads equatorwards so that the discrete aurora has formed arcs before the diffuse pulsating aurora. This results in the well-known display of pulsating patches equatorward of a fairly stable arc or arcs, possibly showing some ray structure. The pulsating phase usually lasts until well after the diffuse aurora has realigned into arcs. The latitudinal extent of the auroral display in the midnight sector decreases drastically during this realignment phase. This late in a substorm there is little difference between the arc that formed from the discrete aurora and the arcs that formed from the diffuse pulsating aurora. At the end of the substorm, the pulsations stop, leaving a uniform weak background south of the discrete auroral arc.

During the realignment phase, black aurora may be observed in the diffuse background. This phenomenon has been observed both in the midnight and the morning sectors and is understood to be the breaking up of a part of the diffuse auroral background, usually the poleward boundary, into discrete auroral arcs.

In the late recovery phase of the substorm, the midnight sector oval shrinks in latitude to a size equal to the latitudinal extent of the oval in the evening and morning sectors.

5.5 Pulsations in the Morning Sector

Sometimes after magnetic midnight, depending on the individual auroral substorm, the display will change from westward drifting to eastward drifting patches. The change is usually fairly abrupt, 10 min to one hour. This, by definition, signals the entrance into the morning sector.

As in the midnight sector, the diffuse aurora in the morning sector consists of pulsating patches and arc segments superimposed on a diffuse background (see Section 4.2). In general, the discrete aurora in the morning sector lines up with the discrete aurora in the midnight sector to form the discrete auroral oval. Thus the discrete aurora in the morning sector is located to the north of the diffuse aurora leaving a dark region between the diffuse and the discrete auroral oval. There is a tendency, however, for the discrete aurora to be more continuously east-west-aligned in arcs in the morning sector than in the midnight sector where it is broken up into arc segments.

Also, pulsating forms in the morning sector differ from those in the midnight sector. Morning sector pulsations are usually relatively large patches pulsating slowly and being stable for several minutes. Large stable patches are by far the most common pulsating forms in the morning sector but streaming fast pulsations and split-streaming have also been observed on occasions, usually during more disturbed magnetic conditions.

The latitudinal extent of the diffuse auroral oval in the morning sector is less than the latitudinal extent of this oval in the midnight sector. Also the shape of the oval is more stable in the morning than in the midnight sector. It does not vary much with magnetic activity, and shows a uniform thickness with smooth poleward and equatorward boundaries. Even when the poleward boundary shows omega bands, this boundary is smooth compared to the poleward boundary in the midnight sector.

The east-west extent of the morning sector depends on the individual substorm. The western boundary is determined by eastward extent of the midnight sector. The DMSP photos have shown that this eastward extent of the midnight sector is highly variable. During strong magnetic substorms the midnight sector auroral oval may even stretch into the morning sunlit region. In this case, no morning sector aurora will be observed. This does not mean, however, that no morning sector aurora exists in these cases. From study of several years of all-sky pictures from Byrd Station and South Pole Station in Antarctica, it has been found that eastward drifting pulsations in the morning sector may continue all the way to the noon meridian or even two or three hours past. Thus, the morning sector auroral oval may at times be located entirely in the sunlit hemisphere. This study was possible due to the high geographic latitude of the two stations. The DMSP photos also show that, whenever observed, the morning sector auroral oval always extends into the sunlit hemisphere.

Drift of pulsating auroral patches in the morning sector is from west to east; the velocity has been measured to lie in the range from 100-300 m/sec.

During the early recovery phase of a substorm, pulsating patches fill the morning sector of the auroral oval. The overall intensity of these patches is much lower than the intensity of the diffuse auroral oval in the midnight sector, as is seen in most DMSP photos covering the major part of the auroral oval in the dark hemisphere (Figs. 5.3 and 5.5). A diffuse background is usually seen in the television data and it may, at times, be strong enough to be visible in the DMSP photos. This background tends to be more intense at the poleward boundary at least late in the recovery phase. However, the diffuse background and the pulsating auroral patches do not always cover exactly the same region; it is usually the background that has the smallest north-south extent.

In the recovery phase the pulsating patches in the morning sector start to realign into arc segments and arcs at the poleward boundary of the oval. At the same time the diffuse background may split up and a second layer of arcs or arc segments is formed. This second layer of arcs and arc segments will still form a background on which the realigning pulsating forms are superimposed. (See also Section 4.3 and 4.5). In this part of the auroral display, both black aurora and multiple layer pulsations are observed.

The recovering arcs in the diffuse auroral oval, are usually diffuse and pulsating. At times, however, the poleward arc may brighten up and form rays and may further develop into an eastward traveling omega band, or a series of omega bands. One example is seen in Fig. 5.5 where the bright arc segment in the late morning sector is believed to be the initial phase of a forming omega band. Data recorded by both the narrow-field and all-sky TV cameras, and reported in Chapter 4, show that an omega band always exhibits fast moving curls and rays and regions of flickering aurora. Omega bands develop from the pre-existing poleward pulsating arc. Change from a diffuse pulsating aurora to discrete rayed arcs and back again is observed in omega bands as it is in the poleward boundary in the midnight sector and behind the westward traveling surge in the evening sector.

After all the pulsating patches have aligned into arcs, the arcs will gradually disappear and at the same time they stop pulsating. At the end of a substorm, the morning sector auroral oval consists of a narrow band of non-pulsating arcs, as do the midnight and evening sectors.

CHAPTER 6

INTERPRETATION AND DISCUSSION OF SMALL-SCALE CHARACTERISTICS OF PULSATING AURORA

6.0 Introduction

Observational data presented in Chapter 4 have permitted the improved morphological description of pulsating aurora in the global framework of the auroral substorm presented in Chapter 5. In addition, the observations have extended the knowledge about the small-scale characteristics of pulsating aurora and its relation to other phenomena. Certain of these characteristics are important because they serve as useful constraints upon, and help provide insight into, possible mechanisms causing pulsating aurora. Other observations, such as those of "black aurora" may not bear directly on pulsating aurora but are of interest in their own right for whatever insight they may provide.

6.1 Frequencies and Amplitudes of Pulsating Aurora

Pulsating auroras are usually defined as constituting a periodic or semi-periodic variation in the light intensity of auroral forms. However, from the television data examined in this work, it is concluded that pulsating auroras are very seldom periodic or even semi-periodic. At best, they are repetitive in the sense that each form usually pulsates more than once or twice and that the "on" periods are of approximately the same length.

Johansen and Omholt (1966) found that the ratio between high-frequency (>0.25Hz) and low-frequency (<0.25Hz) pulsating behavior decreased during the night but with a large spread in individual data points. Their observation agrees well with one of the results of this dissertation showing that pulsating auroras after magnetic midnight are mainly stable patches pulsating slowly compared to the more active pulsations in the midnight sector. Exceptions to this rule may be accounted for by those events in which the midnight sector is extended several hours after magnetic midnight.

No correlations between amplitude and frequency were found by Johansen and Omholt (1966). Although a systematic study was not performed here, the impression from looking at extensive television data is that no such correlation exists.

One observational result is that most pulsations have a frequency ranging from 1.0 to 0.05 Hz and with a peak in the spectrum between 0.5 and 0.1 Hz. Pulsations with periods of several minutes often have been reported in the literature. However, it is concluded that these apparent variations are caused by structures drifting in and out of the field of view of the observing instrument rather than by very slow temporal pulsations of stationary auroral forms. There is a possibility that very slow pulsations, of the order of 10 min, are caused by the formation and disappearance of a large number of patches at the same time. However, this long-period variation is probably caused by the westward drift of torch-like structures and is therefore also a result of spatial rather than temporal variations in intensity.

A limit on the maximum intensity in pulsating aurora has been observed in this work. This limit may not be reached in some pulsating auroral forms, in which case the peak intensity may change from one pulse to the next. However, in many pulsating auroral forms, the limiting intensity is approached in every pulse, giving rise to the characteristic "clipped" appearance of intensity recordings of these events. Close study indicates that the intensity never reaches this maximum, but approaches it as an upper limit, the limit being a few kilorayleighs in N_2^+4278A.

6.2 Shapes and Sizes of Pulsating Auroras

Pulsating aurora exhibits a multitude of variations both in spatial form and in space-dependent time variations. The spatial forms have been divided into three groups;

pulsating arcs, pulsating arc segments, and pulsating patches. Pulsating arcs are always roughly east-west aligned with a width of a few kilometers and a length of several thousands of kilometers. Pulsating arc segments can be aligned in any direction. The width is typically a few kilometers, while the length ranges from one hundred to several hundred kilometers. Pulsating patches may have a very complicated structure, but generally with no particular direction of alignment. With a size ranging from a few kilometers to several hundred kilometers, pulsating patches are the most common pulsating auroral forms. It is clear from the data studied here that there is a continuous spectrum of forms from pulsating patches to pulsating arcs.

The space-dependent time variations have also been divided into three groups; stable, streaming, and split-streaming pulsations. Stable pulsations describe a situation in which the variation in intensity is uniform with time over the whole pulsating form. Streaming pulsations refer to a situation in which the time variation in intensity in some parts of the pulsating form is delayed compared to variations in other parts. These forms give the visual impression of growing in a horizontal direction. Split-streaming is similar to streaming pulsations with the additional feature that the pulsating form splits up into two or more separate forms. Fast auroral waves are a subclass of split-streaming pulsations. Patches, arc segments, or arcs all can exhibit all three forms of space-dependent time variations.

6.3 Background Emissions and Dual Layer Pulsations

The diffuse auroral background often referred to may be present even if not recognized in a particular display. In fact, on several occasions an intense uniform background was only noticed when this background developed internal structure or drifted north or south so that the boundary became visible within the field of view. Therefore, it is reasonable to assume that this diffuse background is present in most or all pulsating displays overhead at College. Lui and Anger (1973), Akasofu (1974), and several others have reported the presence of a diffuse auroral belt or oval, the internal character of which is much less dependent on the magnetic activity than the discrete auroral oval. It is now obvious that this diffuse auroral oval is partly caused by patches and arc segments during an auroral substorm and partly by the uniform background observed.

The phenomenon called double layer pulsations involves a somewhat active and structured background with diffuse, pulsating patches superimposed. There may be two unrelated precipitation mechanisms responsible for such an occurrence. If so, there may exist two different energy spectra in the precipitated particles and thus different altitudes of the two kinds of aurora. The uniform diffuse background is observed to change gradually to a background with fine internal structure, and it seems therefore likely that the energy spectrum is the same for the two kinds of background. From the scale size of the fine internal structure that develops, it seems obvious that the particles involved are electrons. This does not mean that protons and hydrogen atoms are absent, only that most of the light emitted is caused by precipitating electrons. The intensity in this background ranges from several hundred R to a few kR in 4278Å.

6.4 High-Frequency Modulations

High-frequency modulations of pulsating auroral luminosity have been observed in the available television data. In contrast to the main pulsations, high-frequency modulations show stable periodic variations with a frequency ranging from 2 to 4 Hz. With a modulation amplitude ranging from noise level to 20% of the total intensity in most cases, high-frequency modulations are present in more than 50% of all pulsating forms in the midnight and morning sectors. Generally, high-frequency modulation is uniform over the whole, or large portions of a pulsating form. However, if the pulsating auroral form shows internal structure, the modulation will be uniform over individual segments only, even though the slower pulsations are in phase over the whole auroral form. High-frequency modulation may or may not be related to micropulsations in the geomagnetic field. High-frequency modulations might well be generated by some instability related to some wave-particle interaction. Most likely these waves are either electrostatic, or hydromagnetic. In the first case, no micropulsations would be generated, whereas in the second case, they would be generated but probably would not be observable on the ground.

Flickering (Beach et al. 1968) is similar to high-frequency modulation in that it shows fast periodic variations in luminosity superimposed on an existing auroral form. However, the following two important differences distinguish high-frequency modulation from flickering.

1. High-Frequency modulations occur only in low-intensity diffuse pulsating forms, while flickering is associated with bright, discrete auroral forms such as arcs and arc segments in a breakup situation.

2. High-frequency modulations show frequencies ranging from 2 to 4 Hz compared to a frequency range from 7 to 12 Hz for flickering.

However, the similarities between flickering and high-frequency modulation indicate that the mechanisms causing the two phenomena may be of a similar nature.

The possbility that high-frequency modulations and "radar aurora" are in some ways related through some plasma instabilities has been considered. This kind of radar echo occurs in the equatorial region as well as in the afternoon-evening and morning sectors of the auroral oval. Since high-frequency modulations occur only in the midnight and morning sectors, it is concluded that radar aurora and high-frequency modulations are not related phenomena.

6.5 Particle Precipitation in Pulsating Aurora

In addition to the visual observation of the diffuse aurora (Lui and Anger, 1973; Akasofu, 1974) the latitudinal distribution of the precipitated particles has been observed across the auroral oval. Unfortunately no close correlation between satellite-observed particle precipitation and visually observed pulsating structures has been made. Frank and Ackerson (1971), using INJUN 5 satellite data, described the auroral oval precipitation at different local times and different magnetic activities. Caverly (1975) correlated observed particle precipitation from five satellite passes with simultaneous all-sky camera pictures from stations close to the satellite subtrack. All five passes occurred in the evening sector, both during quiet and disturbed magnetic conditions. Caverly agreed with Frank and Ackerson on the existence of inverted V structures and a broad diffuse region to the south of them. Caverly also showed that the inverted Vs corresponded to bright arcs and that the diffuse region is caused by diffuse precipitation south of the arcs.

In addition, Caverly showed that some faint auroral patches and arcs embedded in the evening-sector diffuse aurora in the recovery phase of a substorm were caused by an enhancement of low-energy (<1 kev) particle precipitation, without any high-energy particles (>1 kev) except for the background. From the 16mm all-sky data Caverly was not able to determine whether these auroral forms were pulsating or not.

Brown, et al. (1975) measured the height of pulsating forms just before magnetic midnight. They found an average height of pulsating patches of near 85 km which requires that a high percentage of the precipitated particles have energy in excess of 40 kev. Campbell and Leinbach (1961) found a high correlation between the 3914 Å emission fluctuations, the auroral zone ionospheric absorption of cosmic noise and geomagnetic field micropulsations. Height estimates based upon the known altitude of the cosmic noise absorption indicated a lower border of the pulsating auroral forms of about 90 km. Johansen (1966) also found a high correlation between auroral fluctuations and ionospheric absorption of cosmic noise. The median frequency of the fluctuation spectrum was found to increase systematically with increasing electron energy where the electron energy was found by combining the auroral brightness with the amount of absorption. Hilliard and Shepherd (1966) gave additional evidence for the low altitude of the auroral fluctuations. They discovered a systematic relationship between the auroral brightness and Doppler temperature measured for O atoms. The interpretation given to this relationship is that a brightening of the aurora results mainly from increased energy per particle rather than because of an increased number of particles. This increase will result in lower height, lower temperature and increased brightness. This effect is reported to hold both for large regions of pulsating forms and individual pulsation peaks.

Berkey (1974), using 4278 Å photometer data and 30-36 MHz riometer data, showed a close correlation between ionospheric absorption and auroral emission in the morning sector. All-sky data showed eastward drifting patches which were pulsating as they drifted past the field of view. Berkey also noted that there was a tendency for the luminosity to increase to a certain level before there was any increase in the cosmic noise absorption. This delay he interpreted as an initial increase in the low-energy part of the spectrum and then as a hardening of a more-or-less constant number flux.

Frank and Ackerson (1971), using INJUN 5 satellite data, showed that during magnetically active periods a broad region of high-energy particle precipitation may exist both in the midnight and the morning sectors, usually with a higher number flux in the midnight region. For the morning region they found that the average energy decreased with increasing latitude. However, they did not correlate these data with optical observations of the auroral forms resulting from this precipitation.

On the basis of these data one may safely conclude that pulsating forms usually are caused by high-energy particles. This seems to hold for all pulsating forms in the morning sector, while there may be indications that some pulsations in the midnight and evening sectors are caused by softer particles. The soft particle precipitation reported by Caverly (1975) has not been proven to be associated with pulsating aurora, however, and the observed patches and arcs may not have been pulsating. From the television data used in this study it has not been possible to gain much information on the energy of the particles causing pulsating aurora. However, the data indicate a small altitude extent of pulsating aurora which also supports the conclusion that pulsating aurora is a low-altitude phenomenon and is caused by high-energy particles, individual regions pulsing on in consequence of spectral hardening rather than through increase in the number flux.

Discrete auroral arcs or arc segments have not previously been reported to pulsate. However, observations made here show that there can occur changes in auroral forms, back and forth between stable discrete arcs--usually with rays--and pulsating aurora. Examples of this reversibility are found on the boundary between the discrete and the diffuse aurora; both behind the westward traveling surge in the evening sector, at the poleward boundary in the midnight sector, and in the morning sector. In the morning sector this reversibility manifests itself in the formation of omega bands. Always, the pulsating forms are much weaker than the non-pulsating discrete arc segments.

Assuming that pulsating aurora occurs on closed field lines and discrete aurora on open ones, this change may indicate opening and closing of field lines. Such a conclusion is far-reaching and perhaps wrong. It is more likely that the observed brightening during the transition from pulsating to non-pulsating is caused by the formation of a double layer which will cause an inverted V structure. An inverted V structure can be obtained by adding a constant amount of energy to each precipitating particle (Swift, 1975). The resulting distribution is, for practical purposes, a mono-energetic distribution and may have been brought about by the uniform acceleration of all particles in a previously exponential distribution. Such a uniform acceleration is believed to be caused by an electrostatic double layer or shock (Swift, 1975). This cause is compatible with the data presented by Caverly showing that inverted V structures may have only a moderate increase in number flux but a large increase in energy flux due to the increased average energy compared to the region of diffuse aurora outside of the discrete auroral forms.

The television data reported in Chapters 4 and 5 have repeatedly shown a more or less uniform background in connection with a pulsating aurora display. Observations made by Nielsen and Hallinan (private communications) indicates that this background is located at very high altitude, 200 km or more. This observation indicates a high flux of soft particles (<300 ev) in the background and an enhanced flux of high energy particles (>40 kev) in the pulsating phase. Observation of pulsating displays shows that the background and the pulsating structures are of approximately the same intensity, indicating roughly (within a factor of two or three) the same energy flux in the high and the low energy particles. This rough equivalence in energy flux requires at least two orders of magnitude difference in the number flux between the high- and low-energy particles, the low-energy number flux being the larger. By the formation of a double layer of, say, 5 kev, in a region of diffuse background, the energy flux in the low-energy particles will increase by at least an order of magnitude while the energy flux in the high energy particles will increase at most 10%. The result is that the average energy increases by an order of magnitude, and the lower border of the auroral form decreases in altitude relative to the altitude of the previous diffuse background but increases relative to the altitude of the lower border of pulsating aurora. From this interpretation it is clear that it is possible for the particle population causing the diffuse auroral background to provide the high particle flux in an inverted "V" structure. However, it is not clear why a double layer should occur on field-lines previously occupied by pulsating forms. Once the mechanism producing the V structure comes into play, it produces an aurora so bright that one cannot recognize the effect of the weaker mechanism causing pulsations even if it is still operative.

Johansen and Omholt (1966) reported that pulsating aurora occurs almost exclusively after magnetic midnight. Others have characterized pulsations as a morning sector phenomenon. The data used in this study have shown that, apart from one or more stable arcs to the north, aurora in the morning sector almost exclusively consists of large, slowly pulsating arcs and patches with a stable geometry readily identified as being pulsating aurora. However, in the midnight sector the change from one structure to the other and the rapidly changing temporal character may be so confusing that pulsations are hard to recognize unless the data contain good spatial and temporal resolution. Most data used in previous works have been obtained from photometers which have essentially no spatial resolution and often poor time resolution owing to the slow speed chosen for the recording device. However, none of these difficulties are present in the television data where the main problem is with the lack of information on absolute intensity.

One characteristic that has shown up throughout all of the data is the constant maximum intensity of all pulses in a pulse sequence. At the start of a pulse, the intensity raises rapidly until it reaches its maximum level, which is maintained until the end of the pulse. Also the decrease is usually fairly fast. A schematic diagram of a typical pulse is shown in Fig. 6.1 where part A shows the basic intensity variation and part B shows the same sequence with the addition of high-frequency modulation. It has been interesting to note that the observed intensity never seems to quite reach the maximum level, but approaches it as a limit. This behavior is interpreted in Chapter 7 as being caused by near-strong pitch-angle diffusion approaching strong pitch-angle diffusion as a limit. Strong pitch-angle diffusion corresponds to the greatest possible precipitation rate associated with a given particle density on a geomagnetic field line. How this and other observed features of pulsating aurora relate to suggested precipitation mechanisms is the subject of the next chapter.

6.6 Comment on the Relation of Pulsating Aurora to the Westward Electrojet Current

Pulsating aurora has for a long time been known to be associated with negative bays in the horizontal component of the geomagnetic field (Heppner 1954). Any disturbance in a magnetic field is caused by an electric current, and the westward auroral electrojet current is generally believed to cause a negative bay.

An electric current depends on two quantities: electric field and conductivity. Although not quite constant, the electric field in that part of the ionosphere occupied by the pulsating aurora may be considered constant compared to the time variations in the conductivity. In a plasma restricted by a magnetic field, the conductivity perpendicular to the field depends on high ion and electron densities and high collision frequency. The collision frequency decreases with altitude while the ion and electron densities generally increase with altitude leaving a region of maximum conductivity between 85 and 140 km. Due to recombination of ions and electrons, a high conductivity will generally require a steady energy influx. This downward flux of energy is believed to be carried by auroral particles, but the question remains as to which group of auroral particles. Most discrete auroral forms are caused by a medium-to-high-energy flux, but both the spatial and time distributions of discrete auroral forms are very limited in most cases. The diffuse auroral background equatorward of the discrete auroral oval represents a moderate energy influx over a large area, but the low energy of the particles indicate that they are stopped well above 140 km and therefore do not contribute to the conductivity. However, pulsating auroras which occupy roughly the same areal region as do diffuse auroras are caused by high-energy particles which deposit almost all their energy between 85 km and 140 km, thus contributing to the conductivity. It is therefore reasonable to conclude that a substantial part of the westward auroral electrojet depends on the energy influx associated with pulsating aurora, at least during the recovery phase of the auroral substorm.

6.7 Comment on Black Aurora

Black auroras, or spatially void regions, are common in the late recovery phase of an auroral substorm. They form in the diffuse background that is commonly present in the diffuse auroral oval. The small size of some black auroral forms (<1 km) together with the gyro radius of protons ($\sim$100 m) indicate that the corresponding geomagnetic flux tube may contain an excess of positive charge. That the black aurora represents regions of positive space charge is backed by the observational fact that black auroral arcs at times form curls, and that these curls have a rotation opposite to that of curls in bright auroral arcs known to be caused by excess of negative space change. Two conclusions are drawn; black auroras are regions of near-zero particle precipitation and they represent regions of excess positive charge.

6.8 Comments on Omega Bands and Torch-like Structures

Due to the somewhat similar shape of the omega bands and the torch-like structures, it has been suggested (Akasofu, 1974) that torch-like structures might be formed from omega bands by a nonlinear growth of the latter. However, the following points suggest a different interpretation.

1. Omega bands are observed in the morning sector while torches are a midnight sector phenomena.
2. Omega bands are discrete auroral forms with rayed arc structure and are located at the poleward boundary of the diffuse aurora. A torch, on the other hand, is a part of the diffuse aurora that constitutes an envelope of pulsating auroral patches and arc segments.
3. Omega bands drift or propagate to the east with higher speeds than pulsating patches in the morning sector, while torches drift to the west as a part of the pulsating display in the midnight sector.

4. Torch-like structures are observed more often than omega bands and it is therefore unlikely that torches form from omega bands.
5. In the existing television data there is not a single example of an omega band showing the suggested nonlinear growth to the torch structure.

On a DMSP photo, or a 16 mm all-sky picture, a small torch-like structure may at times be mistaken for an omega band. However, here it is concluded that these are two quite unrelated phenomena.

6.9 Constraints on Mechanisms

A general conclusion reached in this thesis is that pulsating aurora is a very complex phenomenon showing a multitude of variations. Several important new aspects of pulsating aurora have been seen in the television data analyzed in this thesis while other aspects reported previously have been verified. A list of observed phenomena is given below. The list has been arranged roughly according to the importance of each phenomenon as pertaining to possible mechanisms causing pulsating aurora.

1. An upper limit on intensity allowed in pulsating aurora has been observed. Individual pulsating forms may or may not approach this limit which

seems to be the same for all forms in a pulsation sequence. If this limit is reached by a pulsating form, the corresponding intensity recording will have a "clipped" appearance. When the limit is approached, it is approached exponentially.

2. In many or most cases pulsating auroras occur on a diffuse background emission; the on phase of a pulsation can be thought of as an increase above this background within the confines of the flux tube affected. The altitude of the background is substantially higher than the altitude of the aurora when pulsed on.
3. The study of television data have revealed that pulsating auroras are of a non-periodic nature and that periodic pulsations are exceptions.
4. High-frequency (2 - 4 Hz) modulation of pulsation aurora is common in all pulsating forms in the midnight and morning sector indicating an additional mechanism located somewhere between the equatorial plane and the ionosphere.
5. In general the duration of each pulse is more constant than the repetition rate.
6. Sudden changes in the modulation amplitude and the pulsating frequency occur in pulsating forms.

7. A continuous spectrum of pulsating auroral forms does exist, ranging from arcs and arc segments to patches.
8. Likewise, a continuous spectrum of repetitive spatial and time variations occurs ranging from stable through streaming pulsations to fast auroral waves.
9. There is a great variation in the stability of pulsating auroral forms. Some structures are stable for 10-15 min while others last for only a few seconds. At times both forms are present in the same display.
10. Pulsating aurora in the morning sector is confined to a narrow band while in the midnight sector the region is much wider in latitude and exhibits a more irregular poleward boundary, generally with poleward-streaking torch-like structures.

CHAPTER 7

MECHANISMS

7.1 Discussion of Possible Mechanisms Causing Pulsating Aurora

Various mechanisms have been proposed as possibly responsible for pulsating aurora and/or micropulsations in the geomagnetic field. Some of these mechanisms are inconsistent with observations while others are thought to be possible though unproven explanations.

The explanation most often put forth, and rejected, was first mentioned by Størmer (1955), who suggested groups of particles bouncing between the two hemispheres and depositing some energy at each bounce. Dungey and Southwood (1970) tried to explain the very low-frequency pulsations by bouncing protons. However, it is hard to imagine all the modifications to this type of mechanism that would be necessary in order to explain the variety of pulse length and geometrical form observed within one single pulsating structure during an active pulsating display. Still, groups of bouncing particles might explain stable periodic pulsations. However, it has been shown by Shepherd and Pemberton (1968) that there is an inconsistency between observed electron energy and the energy calculated on the ground of the observed pulsation frequency. Cresswell and Davis (1966) showed a discrepancy between the observed and calculated bounce periods and observed drift velocities unless electric fields transverse to B are involved. The strongest argument against this mechanism is that it predicts strictly periodic pulsations, whereas this study has shown that pulsating aurora is not periodic.

From time to time other similar objections have been raised against this theory. It seems most unlikely that pulsating auroras can be caused by groups of mono-energetic particles bouncing between the two hemispheres.

Maehlum and O'Brien (1968) suggested a mechanism by which the perturbation in the geomagnetic field produced by the auroral electrojet also perturbs the pitch angle distribution of the precipitated electrons that are the dominant contributors to the auroral ionization within which it is assumed the auroral electrojet flows. Computations showed that this interaction could cause significant time variations in an initially time-stationary electron precipitation event. The period of these variations depends on the number flux of the precipitated particles with energy greater than 40 kev. For medium to strong electron precipitation events, the calculated periodicity of the variations lies in the range 60-200 sec, indicating that this is a possible mechanism only for very slow pulsations.

The mechanism of Maehlum and O'Brien is one that does not cause pulsations by modulation of the incoming particle stream but rather is a local phenomenon in the ionosphere causing changes in pitch angle distribution which tends to change the mirror altitude. However, there are strong indications from observed phase-shift between fluctuations in precipitated particles with different energies that the actual mechanism is located at the equatorial plane and that the incoming particle stream is modulated. Also, since most observed pulsations have a period of 2-10 sec, it does not seem likely that this mechanism can play a major part in causing pulsating aurora. Furthermore, the observed periodic variations in intensity in the range of 60 to 200 sec are found here to be primarily caused by structures drifting past the field of view of the observing instrument. Consequently, it is reasonable to conclude that perturbation in the geomagnetic field caused by the auroral electrojet does not interact with the pitch angle distribution of the precipitated electrons in a manner that can cause pulsating aurora.

Several authors have shown a close correlation between pulsating aurora and micropulsations in the geomagnetic field. It is conceivable that micropulsations may be related to changes in the ionospheric conductivity caused by pulsations in the precipitated particle flux. Such a change in conductivity will result in a change in the ionospheric currents and subsequent disturbance to the magnetic field. Owing to the different methods used in the observation of optical pulsating aurora and micropulsations, it cannot be expected that the two phenomena should correlate one to one if the connection is through increased conductivity. Even a difference in the observed frequency of the two phenomena can easily be explained from the fact that micropulsations observed in one place may result from the combined effect of several pulsating forms. This is a likely explanation for those micropulsations that do not show a one-to-one correlation to a particular pulsating auroral form. However, in those cases where such correlations do exist, the relationship may be through the mechanism causing pulsating aurora. Coroniti and Kennel (1970a) argued that low-frequency micropulsations can strongly modulate the high-frequency wave amplitude that is responsible for pitch angle diffusion of particles into the loss cone (Kennel and Petschek, 1966). This modulation would cause quasi-periodic pulsations in the precipitated particle flux and thus in the aurora. This theory requires that a steady precipitation already exists, a requirement consistent with the stable background reported here and in other works on pulsating aurora. The idealized model by Coroniti and Kennel (1970a) suggests that the precipitation modulation depends exponentially on the micropulsation amplitude when the micropulsation period is less than the electron precipitation lifetime. High-energy particles would experience a much higher precipitation modulation, a requirement compatible with the observation that pulsations are caused mainly by high-energy particles. This theory also can explain the clipped-amplitude precipitation pulsations that are fairly common in pulsating aurora. Figure 4.3 shows an example where the maximum precipitation is limited perhaps by strong pitch angle diffusion. Since the minimum electron precipitation lifetime is a few hundred seconds on auroral lines of force, Corroniti and Kennel (1970a) concluded that modulations ought to be found only in the 3-300 sec period range. The high-frequency part of this range agrees reasonably well with most frequencies observed in pulsating aurora, excepting for high-frequency modulation and pulsations with periods less than 3 sec. However, there are several weak points in this theory. According to the theory, the weak pitch-angle diffusion increases very rapidly with increasing perturbation periods. For example, if a 10 sec sinusoidal perturbation causes a modulation with a factor of 2, a 100 sec perturbation implies modulation of the precipitation rate with a factor of 2^{10} for the same amplitude of the modulating perturbation. This effect is not observed. In fact, most pulsations do have a relatively constant modulation amplitude, although the duration may vary from one pulse to the next. Another problem with this theory is that the precipitation at any time is dependent on the initial phase of the perturbation, a dependence obviously wrong because the intensity modulations would be negative for all times if the disturbance started with a negative pulse.

Haugstad (1974) pointed out these problems and also introduced the concept of relaxation time of the electron velocity distribution to suggest a more self-consistent theory. His solution to the problem is independent of the perturbation frequency so that the low frequencies no longer present any problem. The degree of modulation depends only upon relative perturbation amplitude and the size of the loss cone. Also, each point in the perturbation phase corresponds uniquely to one value of the precipitation rate, irrespective of how the perturbation starts; perturbation pulsations are in phase with the magnetic disturbance. With these modifications the Coroniti-Kennel theory seems to be able to explain many of the observed features in the pulsating aurora display. Firstly, the Coroniti-Kennel theory calls for a low-energy, steady background precipitation which can be identified as the diffuse auroral background at times present during pulsating displays. Secondly, the observed limit on the maximum intensity is believed to correspond to near-strong or strong pitch-angle diffusion in the precipitated particle population, and such a limit appears in our data. Also the constant maximum intensity observed in all forms of a pulsating display indicates a connection between pulsating aurora and this limit on the precipitated particle fluxes. However, some patches, or parts thereof, may have a maximum intensity less than this upper limit, which may by a consequence of weak pitch-angle diffusion. If the pitch-angle diffusion is weak, the maximum intensity in pulsating forms may change from one pulse to the next. It is conceivable, of course, that the mechanism responsible for the pitch-angle diffusion is not the one suggested by Kennel and Petscheck (1966).

Etcheto et al., (1971) have measured simultaneously a periodic VLF emission associated with a hydromagnetic (ULF) emission and a periodic fluctuation of the flux of trapped particles. Estimations of diffusion rate indicated results within the framework of Coroniti and Kennel's theory and therefore are supportive of the correctness of that theory.

In a later paper, Coroniti and Kennel (1970b) suggested that Alfvén waves are responsible for precipitation modulation at auroral latitudes. They concluded that large scale-lengths parallel to, and small lengths transverse to, the magnetic field, together with the low frequency are consistent with the interpretation of micropulsations being observed drift waves. Drift instabilities derive their energy from spatial gradients in the distribution of resonant particles. It is suggested, in this case, that the instability is driven by the sharp electron thermal gradient at the inner edge of the electron plasma sheet. Calculations showed that fast growing waves should have a period 4 to 25 sec which is consistent with most observations of pulsating aurora and micropulsations during substorms. Assuming that the eigen oscillation is a standing wave, the energy will propagate in a longitudinal direction. This propagation velocity was found to be 10 km/sec which, mapped from the equatorial plane onto the ionosphere, represents approximately 1 km/sec drift from west to east. This is somewhat high compared to observed drift velocities of a few hundred meters per sec.

D'Angelo (1969) also explained pulsations in the auroral light by a drift wave causing modulation of the steady particle flux that exists most of the time in the auroral oval during a magnetic substorm. He argues that the universal instability is driven by a density gradient in the hot plasma in the anti-solar magnetosphere at R_E=6. It is assumed that, at least part of the time, the density decreases with distance away from the earth.

D'Angelo (1969) and Coroniti and Kennel (1970b) agree that the pulsations should be in the form of somewhat north-south elongated patches drifting from west to east along parallels of geomagnetic latitude. Also they agree that the drift velocity should range from 500 m/sec to 5 km/sec and that the size of the individual patches should be in the range 20 km to 200 km. D'Angelo (1969) found a growth rate ranging from somewhat less than a minute to several minutes, whereas Coroniti and Kennel (1970b) found that the fastest growing wave should have a period of the order of 10 sec.

The observational fact that the pulsating period in eastward drifting patches generally lies between 2 and 15 sec indicates that the gradient responsible for the waves may be different from that assumed in these two papers if the theories of D'Angelo and Coroniti and Kennel are to be accepted. If this picture is correct, Alfvén waves may be responsible for some of the features in pulsating aurora, most likely the stable, moderately slow pulsating patches drifting east in the morning sector. The width of the auroral oval in the morning sector is also consistent with the dimension of the inner edge of the electron plasma sheet ($\sim$5000 km). However, the complexity of the different kinds of pulsating aurora makes it unlikely that this mechanism alone can be responsible for all intensity fluctuations in auroral displays. However, other mechanisms most likely will in some way be related or similar to that of D'Angelo and Coroniti and Kennel.

Hasegawa (1969) suggested that a 300 sec period in proton precipitation is caused by a drift wave created by ion drift perpendicular to the magnetic field. In several other papers, different micropulsations in the geomagnetic field have been related to plasma instabilities with suitable growth rates. Although in most cases these micropulsations have not been related to variations in particle precipitation, there are clear indications that such a relationship exists.

A 2-4 Hz high-frequency modulation in pulsating aurora has been identified and is reported in this study. As far as is known, no theoretical work has predicted this phenomenon. Perkins (1968), however, suggested that a mono-energetic electron flux at an energy $E_0 \sim 10$ kev would make the ionosphere unstable to electrostatic plasma waves. If the flux exceeds a critical value, the waves can grow to an amplitude large enough to cause stochastic acceleration of a few electrons to energies $\sim$40-100 kev. The time scale of this growth would be $\sim 10^{-2}$ sec. However, the repetitive rate of such an acceleration would depend on the restoration time of the monoenergetic flux which is calculated to be of the order of 10^{-1} sec. This theory has been used to explain the 7-13 Hz fluctuation in the particle precipitation (Evans, 1967) associated with flickering aurora reported by Beach et al., (1968). Possibly this or an analogous mechanism can be responsible for high-frequency modulation in pulsating aurora. The lower frequencies might be explained by a slower restoration of the mono-energetic flux after each pulse. However, the high-frequency modulation is usually uniform over a whole pulsating structure which can be of size 20 to 200 km. The observed size distribution disagrees with Perkins' (1968) theory predicting a size of the order of 1 km across magnetic field lines. For this reason it is unlikely that electrostatic plasma waves can be responsible for high-frequency modulations in the particle flux causing pulsating aurora. Therefore another wave mode will have to be found.

A consistent theory of pulsating aurora mechanisms is likely to be divided into two groups, the major one consisting of one or more mechanisms explaining all large-scale and slow pulsations (>1 sec) and one single mechanism explaining the high-frequency modulations (2-4 Hz). The velocity distribution of the particles involved in the high-frequency modulation is not known, but assuming the distribution is not too sharply peaked at a certain velocity, a good argument can be made that the high-frequency modulation must have its origin within 2-3 Re above the ionosphere (Evans, 1967). On the other hand, the mechanisms responsible for the slow pulsations are frequently suggested to be located in the vicinity of the equatorial plane (Bryant et al., 1971). (See Section 6.5).

Combining the observations presented here with the theoretical developments to date, the following causes of pulsating aurora seem most likely. Pitch angle diffusion of particles into the loss cone takes place in the equatorial region. This steady pitch angle diffusion is modulated by some form of instability-generated wave, most likely the one proposed by Coroniti and Kennel (1970a) and as modified by Haugstad (1974). The pulsations in the precipitating electron flux, thus generated, are then high-frequency modulated by a microinstability located somewhere on the geomagnetic field line between the equatorial region and the ionosphere. This instability may be activated by free energy in the velocity distribution of the particles created by strong pitch angle diffusion which is interacting strongly with particles in a certain energy range. A detailed theory for the high-frequency modulation is not available, but it is expected to be analogous to the one proposed by Perkins (1968), although the wave will probably be in another mode.

CHAPTER 8

SUMMARY AND RECOMMENDATIONS

8.1 Summary

The work on this dissertation was begun with three objectives in mind:

1. To give a detailed description of the small and medium scale characteristics of pulsating aurora, based on the extensive amount of new data available from all-sky and narrow-field television systems and DMSP satellites.
2. To give a comprehensive morphological description of the global distribution of pulsating aurora, utilizing the framework of the auroral substorm.
3. To apply the new results to test various mechanisms suggested as the cause of pulsating aurora.

Pulsating auroras have been found to be the second most significant grouping of auroras in terms of temporal and spatial distribution and are surpassed only by the quiet east-west-aligned arc that forms the auroral oval during magnetically quiet times. However, it is the auroral substorm that poses the most interesting questions concerning the aurora, and at such times, pulsating auroras are the most widespread part of the display.

Pulsating auroras are found throughout the whole diffuse auroral oval in the midnight and morning sectors during the recovery phase of an auroral substorm. Although infrequent, pulsating auroras occur also in the evening sector, but here only in the form of arcs or east-west-aligned arc segments. A schematic diagram (Fig. 5.2) has been constructed to show the distribution of pulsating aurora in a typical auroral substorm. Although it is known that pulsating aurora occurs in the day sector in a region extending to magnetic noon, the shape of the pulsating region there is largely unknown. Recent DMSP photos indeed indicate that both the discrete and the diffuse aurora in the noon sector exhibit quite complicated large-scale structures. The discrete aurora is an extension of the polar cap auroral arcs; the diffuse aurora is located equatorwards of these discrete arcs. However, only a few pertinent DMSP images are available and no firm conclusion has been drawn.

Omega bands have been observed on several occasions and have been identified as bright arc segments at the poleward boundary of the diffuse auroral oval in the morning sector. Typically, omega bands show ray structures and flickering.

Torch-like structures have been identified as part of the diffuse auroral oval exhibiting pulsating patches and arc segments. It is concluded that torches are not closely related to omega bands; torches being located in the midnight sector and drifting westwards, while omega bands propagate eastwards in the morning sector.

It has been verified that auroral forms in the evening and midnight sectors drift from east to west while, in the morning sector, the drift changes to eastward. This change in drift direction is usually fairly abrupt and occurs sometime after magnetic midnight. It is believed that the change takes place at the boundary between the expanded auroral oval in the midnight sector and the usually much narrower oval in the morning sector.

It is reported in the literature that a diffuse background invariably accompanies a pulsating auroral display. Due to the impossibility of obtaining any absolute intensity measurements from the data examined here, it has not been possible to be certain that the background always exists, but the data strongly suggest that a background exists most or all of the time. On the other hand, it has been found that where the background is present, it is not always uniform and diffuse. A background consisting of a high density of small patches and arc segments has been observed on several occasions. It is suggested that two different mechanisms are operating on the same field line and that they affect particles with different energies--one produces the steady background; the other causes the pulsations. Black auroral forms have also been identified in the diffuse auroral background. Black aurora usually appears as small east-west-aligned patches; also, black single and multiple arc and arc segments have been observed. There even exist examples of black arcs that develop into strings of black curls. It is concluded that the black aurora is involved in the formation of multiple discrete arcs at the poleward boundary of the diffuse aurora in the late recovery phase of an auroral substorm. The observational fact that black auroral patches, at times, form and disappear on a time scale comparable to the period of normal pulsating aurora, may be interpreted as pulsations in black aurora.

Pulsating aurora takes on a great variety of forms and a simple classification scheme has been worked out in which it is possible to identify every pulsating structure according to its spatial and temporal variation. The pulsating forms have been divided into three groups: arcs, arc segments and patches. Each of these three kinds of pulsating structures may show any of the following spatial and temporal variations in intensity: stable pulsation, streaming pulsation, and split-streaming pulsation. Superposed on the behavior described above is high-frequency modulation, which the recognition of may be one of the most important findings of this work.

With a frequency ranging from 2 to 4 Hz, high-frequency modulation has turned out to be the most stable feature in pulsating auroral forms and is found to be present in all kinds of pulsating aurora except for stable pulsating arcs that sometimes occur in the evening sector just before breakup. With a modulation amplitude ranging from noise level to almost 100% on rare occasions, these modulations are present in 50% or more of the pulsating auroral forms.

Several examples of frequency spectrums in different forms of pulsating aurora have been presented in the literature. These examples show that most pulsations have a period ranging from 1 to 15 sec. By simple counting, the data available have been checked and found to be primarily within this period range; no further frequency analysis has been attempted. However, it has been noted that the pulsations usually are fairly irregular and can best be described as repetitive. The high-frequency modulation is an exception in that it is relatively periodic, even though the modulation amplitude may change from one pulse to the next.

In reviewing the different mechanisms possibly responsible for pulsating aurora, it was concluded that a group of electrons or protons bouncing between the two hemispheres could not be responsible for pulsating aurora. A mechanism suggested by Maehlum and O'Brien (1968) has also been rejected. This hypothesis predicts that the perturbation in the geomagnetic field produced by the auroral electrojet also perturbs the pitch angle distribution of the precpitated electrons that are the dominant contributors to the auroral ionization within which it is assumed the auroral electrojet flows. This positive feedback would cause variations ranging from 60 to 200 sec.

The most likely explanation for pulsating aurora was given by Haugstad (1974) who modified a theory by Coroniti and Kennel (1970) based on whistler wave-generated pitch angle diffusion (Kennel and Petschek, 1966). In short, it is argued that low-frequency micropulsations can strongly modulate the high-frequency wave amplitude that is responsible for pitch angle diffusion of particles into the loss cone. This mechanism is compatible with several observed aspects of pulsating aurora, one of them being the limited intensity of pulsation aurora. The upper maximum intensity is thought to result in the limit represented by strong pitch-angle diffusion. By implication, this theory also serves as the mechanism generating the low-frequency micropulsations that determine the shape and behavior of the pulsating patches, as contrasted to that shape being determined by a flux tube with an anomalous particle population drifting in the magnetosphere.

8.2 Recommendations

There are a multitude of courses that may be attempted in order to increase the understanding of pulsating aurora and the mechanisms involved. Suggestions of promising directions are the following:

1. In this work, a combination of all-sky and narrow-field TV cameras has been very useful, although a high-frequency, narrow-field (1^{o} - 2^{o}) photometer system attached to the narrow-field TV camera would have been advantageous. Accurate intensity information, combined with high time and spatial resolution would be gained. This instrumental addition is fairly simple and is recommended for further observational work in this field, both in conjunction with DMSP satellite data and the television itself.
2. Three things are important to know in order to get a better understanding of the mechanisms causing

pulsating aurora. From the energy distribution and the time-variation of the precipitating particles, the location of the source can be found. Measurements of the particle population and the wave spectrum at this location would further add to the understanding of the mechanisms involved. Satellite and rocket observations coordinated with ground observations are needed to obtain the measurements.

3. Theoretical knowledge about the mechanisms causing pulsating aurora is, at present, mostly lacking. No attempt has been made to explain the great variety of shapes of pulsating auroral patches and arcs already recognized in earlier works. In addition, there are the different new characteristics reported in this thesis. The fact that there is a continuous spectrum of forms suggests a set of mechanisms interacting strongly with each other. A substantial effort is needed in order to bring the theoretical knowledge up to the level of the morphological knowledge.

4. The high-frequency modulations reported in this thesis are thought to be caused by modulation of a more-or-less monoenergetic particle precipitation

perhaps located close to the ionosphere. This mechanism may be largely independent of the mechanism responsible for the slower pulsations. Due to the simple characteristics of these high-frequency modulations, the mechanisms responsible might be easily found. Rocket or satellite measurements of the particle population and the wave spectra in the altitude region 1000-15,000 km should give an indication of the direction in which theoretical work should be taken.

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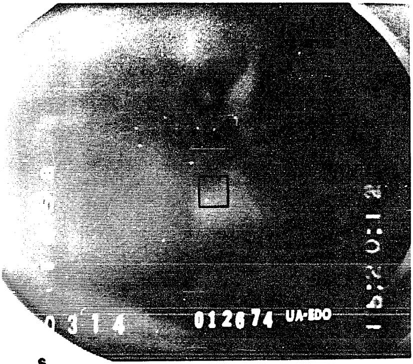
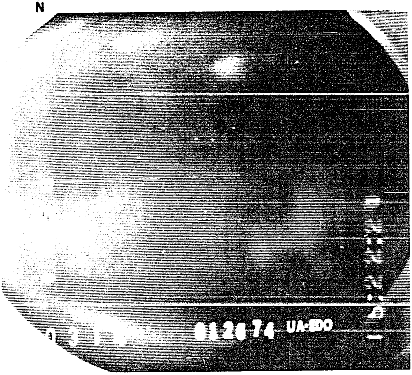
Figure 4.1

All-sky television data from 20 Jan 1974 15:15 UT. Parts A and B show the all-sky television screen at 15:20:12 and 15:22:21, respectively. Eastward drift of the pulsating auroral forms is recognized by comparing the two images.

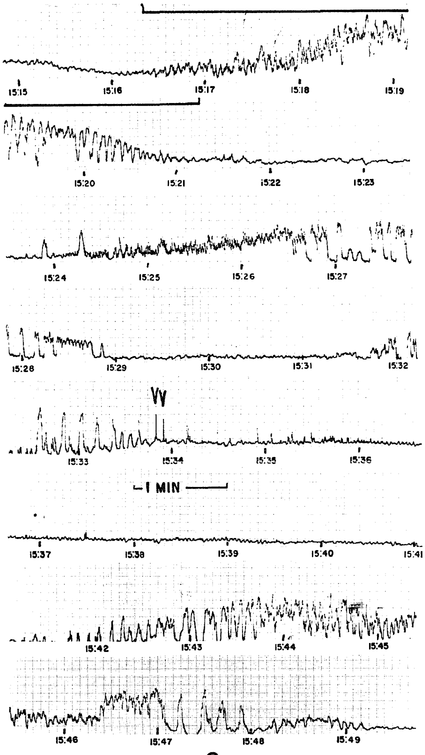
In these two pictures and all following images of television data north is at bottom and east is to the right. The vertical and horizontal numbers to the left in these images represent respectively the elevation and azimuth of the viewing direction (in tenths of degrees) of the narrow field television camera normally taking simultaneous pictures; these numbers do not pertain to the view-direction of the all-sky television camera. In the lower center of the images the month, date, and year, along with the identification letters of the station (UA-EDO) are given. EDO refers to the Ester Dome Observatory near Fairbanks. The vertical numbers to the right gives the universal time. The black rectangle in the center of picture A shows the size and location of the analyzing window used to obtain the tracings shown in Part C. Part C shows an intensity trace made from the all-sky television recording. Relative intensity was recorded at the magnetic zenith which is approximately in the center of the field of view over the areas outlined by the rectangle in Part A. The intensity trace shows slow variations, ca 5 min, caused by the drift of forms past the recording "window." One such pulse is marked with a bar in the upper part of the intensity trace, Part C. Abrupt changes in the pulsating amplitude and frequency can be seen at 15:23:45 and 15:28:25. Two single short pulsations of approximately 0.2 sec duration occurred at 15:33:50 and 15:33:55, locations marked by downward-pointing arrows.



A



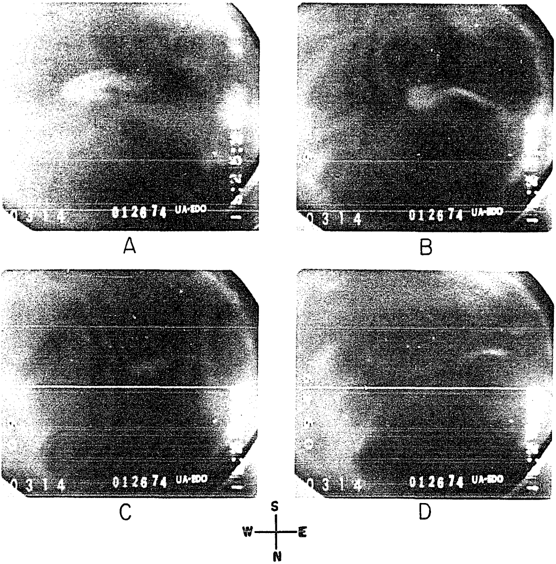
B


15:15
15:16
15:17
15:18
15:19
15:20
15:21
15:22
15:23
15:24
15:25
15:26
15:27
15:28
15:29
15:30
15:31
15:32
VY
15:33
15:34
15:35
15:36
1 MIN
15:37
15:38
15:39
15:40
15:41
15:42
15:43
15:44
15:45
15:46
15:47
15:48
15:49

C

Figure 4.2

All-sky television data from 26 Jan 1974. The images A, B, C, and D (15:25:22 through 15:29:48) show eastward drift of a stable pulsating patch. This series of pictures was used for drift measurement from west to east. (See also title to Fig 4.1)



012674 UA-EDO
A
B
C
D
S
W
E
N

Figure 4.3

Intensity recording from all-sky television data from 2 March 1973, 11:07:00 through 11:11:10. The display showed westward drifting patches. The intensity trace shows fairly stable pulsations part of the time with periods ranging from 2 to 5 seconds. Low-amplitude, high-frequency modulations can be seen several places in the data, and the periods of highest modulations are marked with a bar (11:09:51 - 11:09:58). (See also title to Fig 4.1)

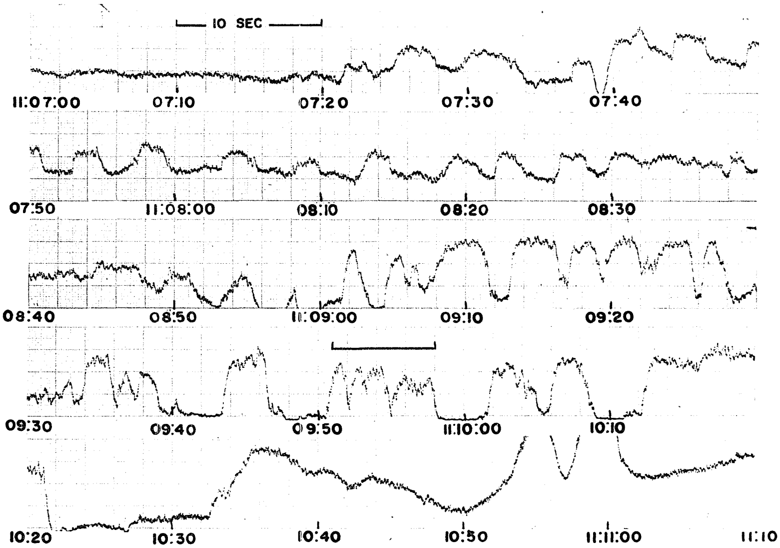
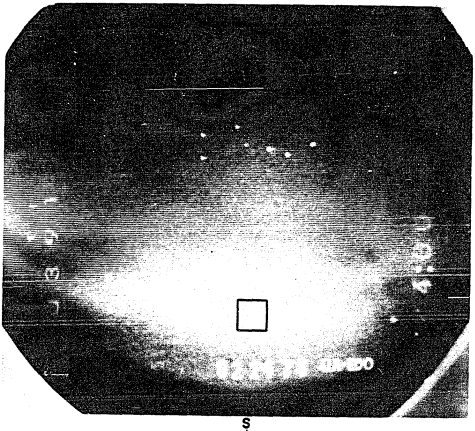
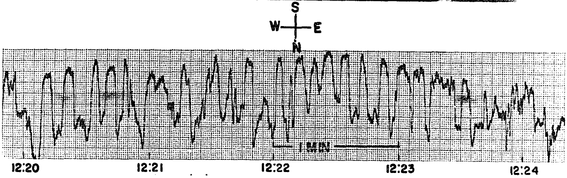

10 SEC
11:07:00
07:10
07:20
07:30
07:40
07:50
11:08:00
08:10
08:20
08:30
08:40
08:50
11:09:00
09:10
09:20
09:30
09:40
09:50
11:10:00
10:10
10:20
10:30
10:40
10:50
11:11:00
11:10

Figure 4.4

All-sky television data from 24 Feb 1974, 12:20 through 12:24. The all-sky television picture (12:24:00) shows a broad diffuse and structureless arc. The amplitude modulation in the intensity recording is less than 100% and variable. Most of the time the pulsating periods are relatively stable at 5-10 sec, with a few pulsations of shorter duration occurring near 12:23:55.





S
W
E
N
1 MIN
12:20
12:21
12:22
12:23
12:24

Figure 4.5

All-sky television data from 16 March 1974, 13:14 through 13:19. The image is of discrete arcs on a diffuse background. Fairly strong streaming of the arcs in a north-south direction was observed in the original data. The arcs are located to the south of zenith, while some stable rays are seen to the north. The intensity recording shows irregular pulsations caused by the streaming arcs.

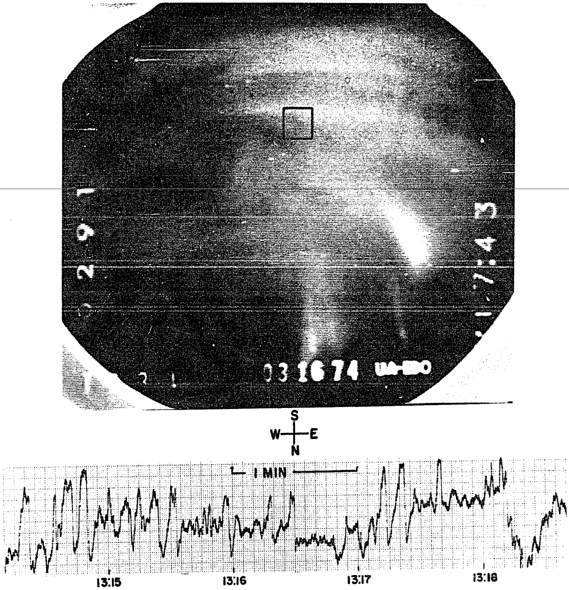

031674
S
W
E
N
1 MIN
13:15
13:16
13:17
13:18

Figure 4.6

All-sky television data from 24 Feb 1974. The series of pictures, one each second from 11:26:20 to 11:26:27, shows one pulse of a streaming pulsating patch. A fairly stable core is seen in the lower part of the picture. The streaming is in the southward direction, and the size of the patch is maximum in pictures C and D. The decay phase in this case is longer than the growth phase. Also note in picture C that the streaming patch and the patch in the upper right corner seem to be separated by a dark region of constant width. Only one of the patches show pulsations in this sequence.

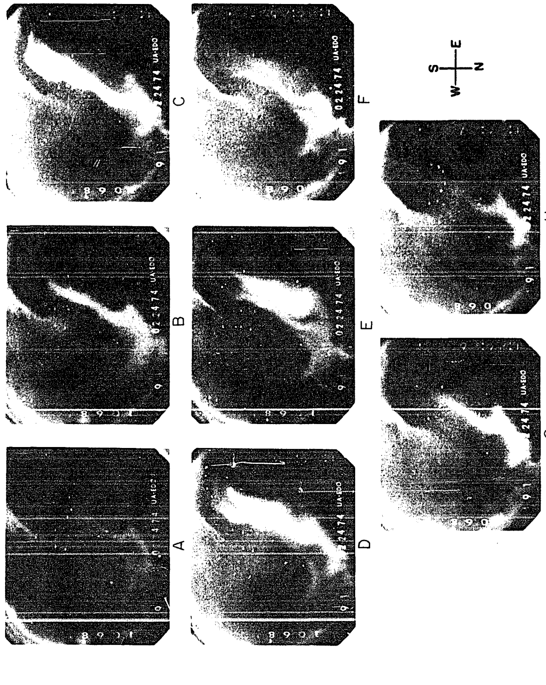
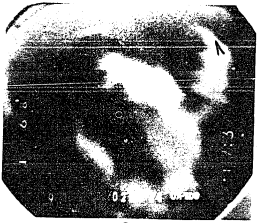

A
B
C
D
E
F
G
H

Figure 4.7

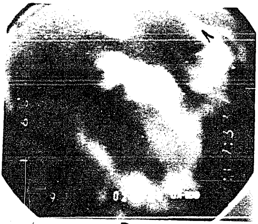
All-sky television data from 24 Feb 1974 containing one picture each second from 11:17:30 through 11:17:34. A complicated growth phase of a streaming patch is seen in the pictures A through E. The core of the streaming patch is located in the upper right hand corner in picture A. This patch is marked by an arrowhead in each picture. The sequence of pictures shows the patch streaming out first in a southward direction and then, in C through E, the streaming direction changes from southward to westward. Part E shows the patch after it reached its maximum size. The decay phase was more uniform throughout the patch but showed some reverse streaming.

A

B



C



D

E

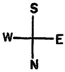


Figure 4.8

Intensity recording made from all-sky television data from 22 March 1973 from 12:14:00 through 12:16:40. Semi-periodic pulsations with a low-amplitude high-frequency modulation superimposed are present throughout the whole time interval. Note that high-frequency modulations are not present in all pulses in this sequence.

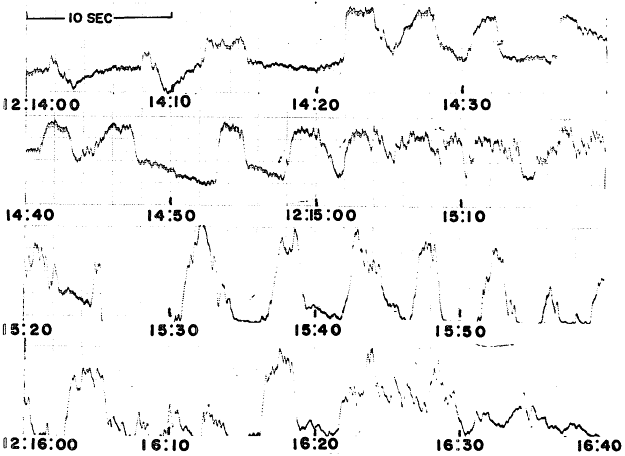
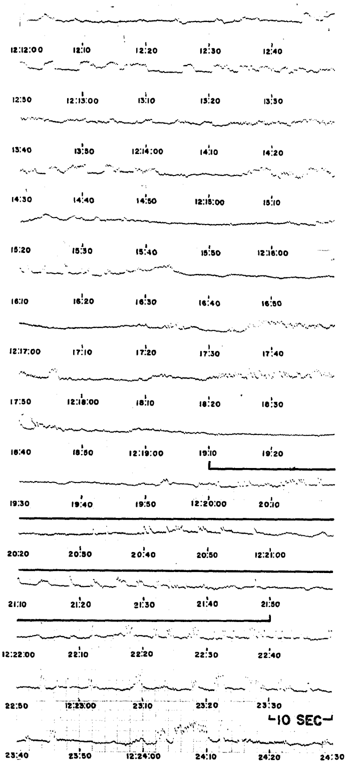
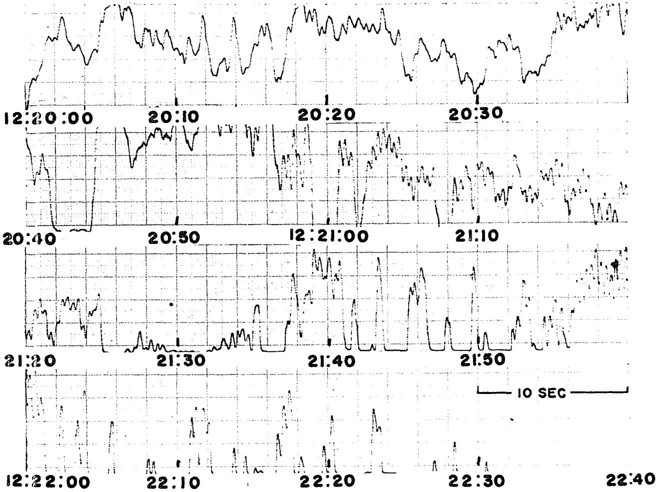

10 SEC
12:14:00
14:10
14:20
14:30
14:40
14:50
12:15:00
15:10
15:20
15:30
15:40
15:50
12:16:00
16:10
16:20
16:30
16:40

Figure 4.9

An Intensity recording made from all-sky television data from 22 March 1973 from 12:12:00 through 12:24:30. Part A is obtained by placing the analysis window so as to record the intensity variation over an area 10 by 10 km in the magnetic zenith. The tracing in Part B corresponds in time to the portions of Part A indicated by bar drawn over the trace there. In Part B the intensity over the entire screen is recorded. Large-amplitude high-frequency modulations are seen in parts A and B. Note the development in part A from fast pulsations without any visible high-frequency modulation to a regular pulsation with unusually large high-frequency modulations at time 12:22:30. Comparison between A and B illustrates the complexity of an intensity trace when the intensity is integrated over an area containing many patches pulsating independently.


12:12:00 12:10 12:20 12:30 12:40
12:50 12:13:00 13:10 13:20 13:30
13:40 13:50 12:14:00 14:10 14:20
14:30 14:40 14:50 12:15:00 15:10
15:20 15:30 15:40 15:50 12:16:00
16:10 16:20 16:30 16:40 16:50
12:17:00 17:10 17:20 17:30 17:40
17:50 12:18:00 18:10 18:20 18:30
18:40 18:50 12:19:00 19:10 19:20
19:30 19:40 19:50 12:20:00 20:10
20:20 20:30 20:40 20:50 12:21:00
21:10 21:20 21:30 21:40 21:50
12:22:00 22:10 22:20 22:30 22:40
22:50 12:23:00 23:10 23:20 23:30
10 SEC
23:40 23:50 12:24:00 24:10 24:20 24:30

A


12:20:00
20:10
20:20
20:30
20:40
20:50
12:21:00
21:10
21:20
21:30
21:40
21:50
10 SEC
12:22:00
22:10
22:20
22:30
22:40

B

Figure 4.10

All-sky and narrow field television data from 14 March 1975 between 11:22:50 and 11:23:35. The all-sky data showed diffuse pulsating arc segments on a diffuse background and a rayed arc to the north. Part A is from this sequence at time 11:22:58. The narrow field TV Part B showed almost uniform pulsations over the whole field of view. This frame is also for time 11:22:58. The intensity recordings in C are from the narrow field (upper trace) and the all-sky (lower) and show that the high-frequency modulation can easily be identified in the narrow field data, but not at all in the all-sky data.

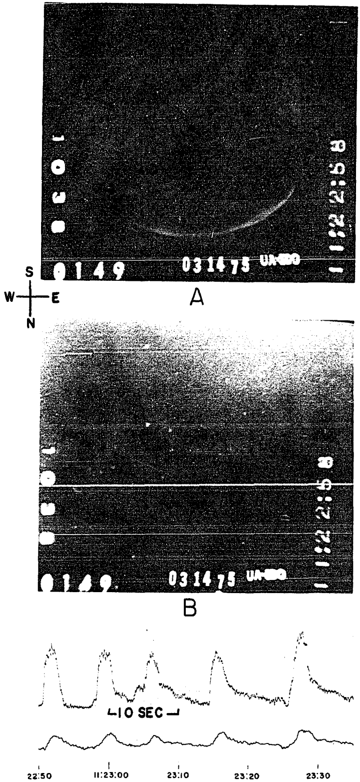

S
W
E
N
0149
031475
A
B
10 SEC
22:50
11:23:00
23:10
23:20
23:30
C

Figure 4.11

Intensity recordings from narrow field television data. Part A is from 10 Feb 1975 between 13:34:30 and 13:37:20; Part B is from 16 Feb 1975 between 12:04:30 and 12:06:10. Both recordings are from displays with a high degree of fine structure and both show high-frequency modulations.

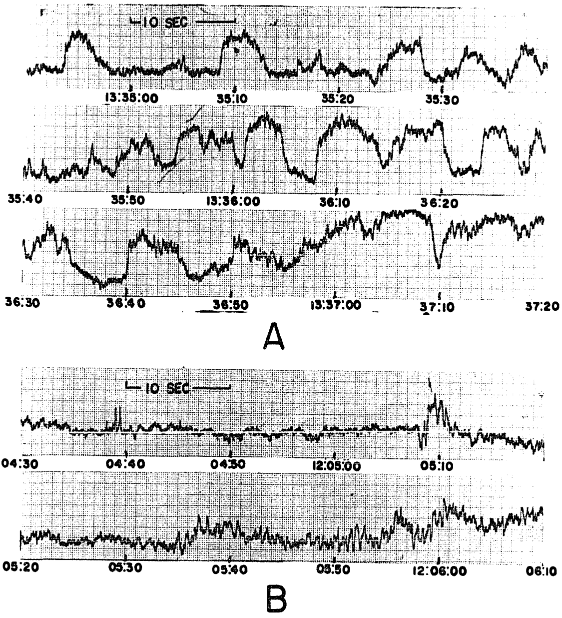
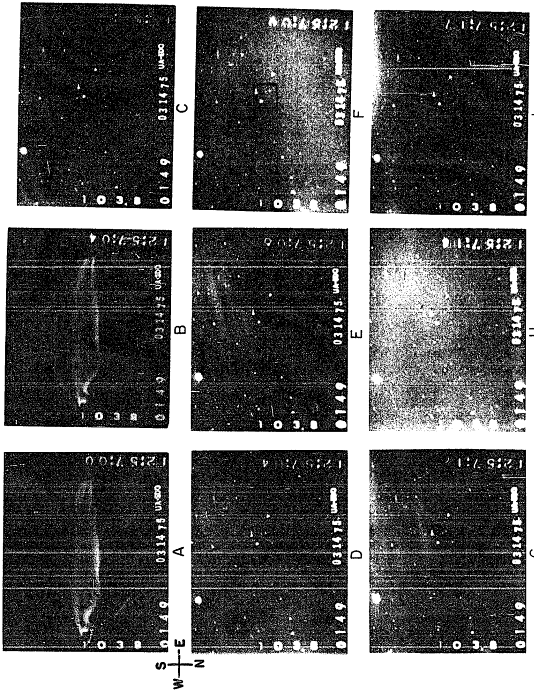

10 SEC
13:35:00
35:10
35:20
35:30
35:40
35:50
13:36:00
36:10
36:20
36:30
36:40
36:50
13:37:00
37:10
37:20
A
10 SEC
04:30
04:40
04:50
12:05:00
05:10
05:20
05:30
05:40
05:50
12:06:00
06:10
B

Figure 4.12

All-sky and narrow field television data from 14 March 1975. Parts A and B show the display in the all-sky televison at 12:57:00 and 12:57:04, respectively. The other parts contain frames from the narrow-field TV at the times shown on the right-hand side of each photograph. Note that no structure in the background can be seen in Parts A and B. The series of pictures from the narrow field TV camera (C through I) show pulsations at times of alternating maximum and minimum intensity. Both the structure and the change in the background is obvious in Parts C, E, G, and I. The intensity trace from the narrow-field TV for this sequence is shown in Parts J and K, the location of the analysis window used to obtain these traces is shown on Part F. No high-frequency modulation was visible in the data between 12:47:00 and 12:47:50. The intensity trace from 12:58:10 to 12:59:00 (Part K), however, shows that the pulsations changed to being more irregular and having fairly large high-frequency modulations of the intensity.


A
B
C
D
E
F
G
H
I

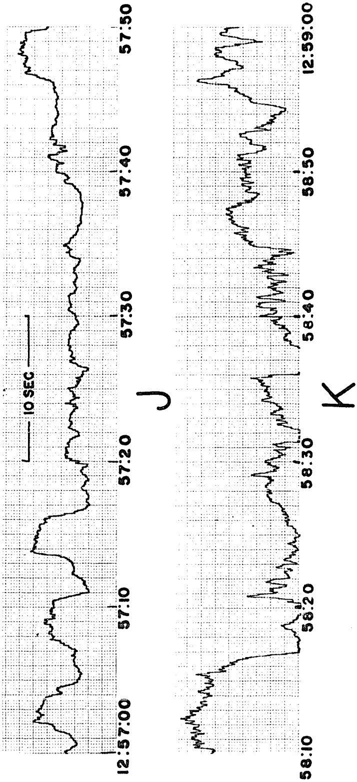
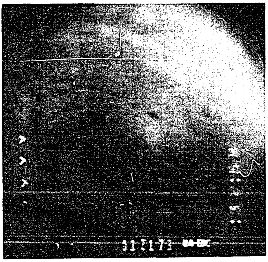
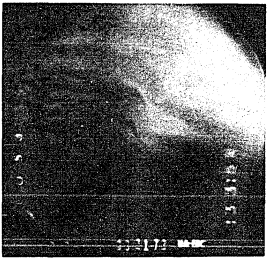
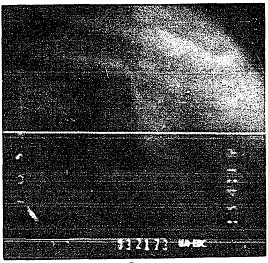

10 SEC
12:57:00
57:10
57:20
57:30
57:40
57:50
J
58:10
58:20
58:30
58:40
58:50
12:59:00
K

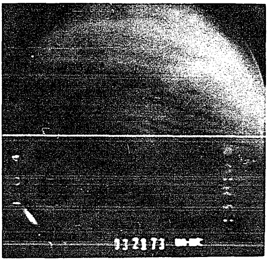
Figure 4.13

All-sky television data from 21 March 1973 at the times 10:32:58, 10:33:54, 10:34:19, and 10:38:06 Parts A, B, C, and D, respectively. Parts A, B, and C show formation of black auroral patches on a relatively uniform background with diffuse arcs located to the south. Also note in B and C the simultaneous northward shift of the diffuse arcs and the strings of black patches. At 10:38:06 (Part D) the black patches had started forming black arcs.


A


B


C


D

S
W E
N

Figure 4.14

Narrow field television data from 7 Feb 1975.

Part A (12: 51:04) and Part B (12:51:13) show two rows of black spots that appeared and lasted for only a few seconds each. Note the interconnecting curl form in Part B and the alternating dark and bright bands (arcs) to the south.

Parts C, D, E, and F, 12:52:56, 12:53:03, 12:53:09, and 12:53:11, respectively, show the drift of a black auroral arc segment in the eastward direction.

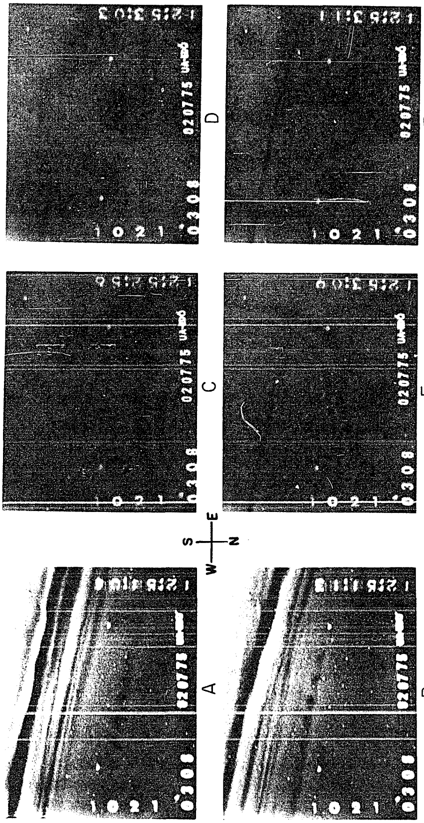
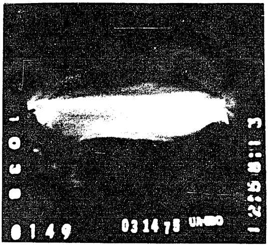
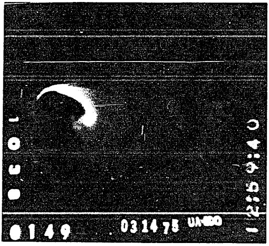

A
B
C
D
E
F
W
S
E
N

Figure 4.15

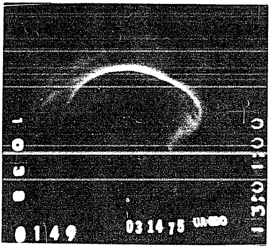
All-sky television data from 14 March 1975. The series of pictures A, B, and C (12:58:13, 12:59:40, and 13:01:00, respectively) show the eastward travel of an omega band along the northern boundary of the diffuse aurora. As the omega band moves through the field of view, the pre-existing arcs change from diffuse pulsating to active rayed bands with flickering immediately to the north. Note the rays in the leading edge of the omega band in Part C.



A



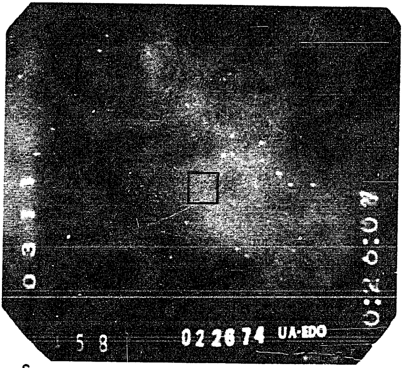
B



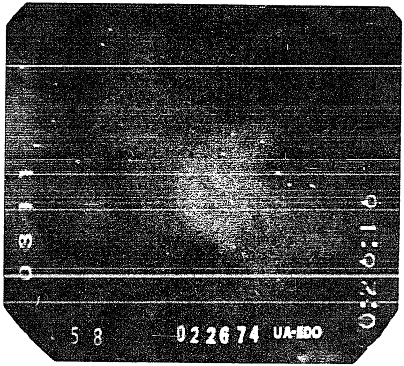
C

Figure 4.16

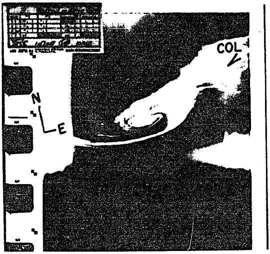
Parts A and B contain all-sky television data acquired during the pass of a DMSP satellite on 26 Feb 1974. Picture A (10:26:07) and B (10:26:16) show weak diffuse auroral patches over College at the time the satellite passed to the west of the station. C shows the DMSP image wherein College is located just inside the right-hand edge of the picture at the position of the arrowhead. A westward-traveling surge is followed on its eastward ride by a broad region of diffuse aurora. The diffuse white regions at left, along the top edge and at right center are caused by sunlight entering the scanner instrument. The intensity trace D (10:25:00 to 10:29:10) shows fairly fast and irregular pulsations with low modulation amplitude. There is some indication of high-frequency modulations in the intensity recording.



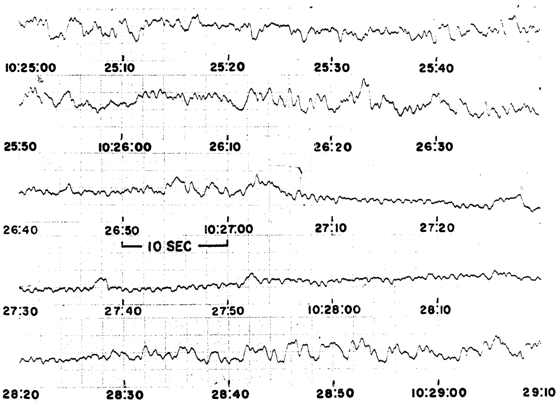
A



B


COL
N
E

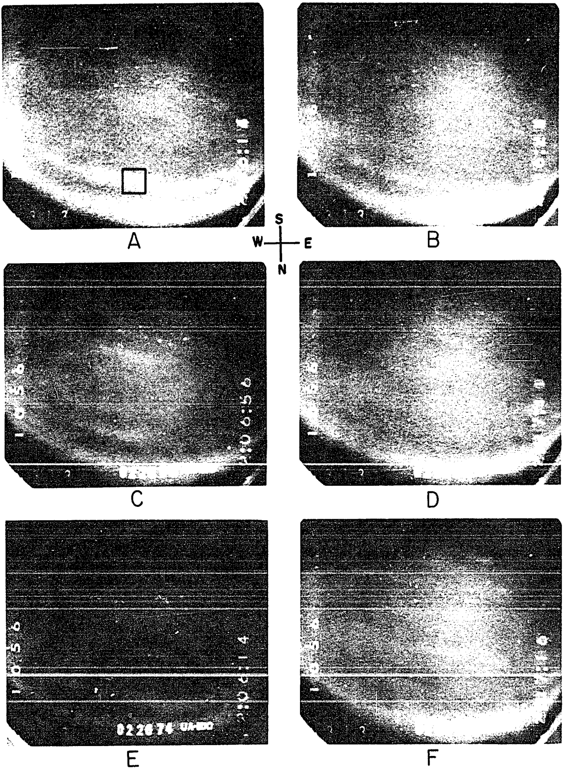
C

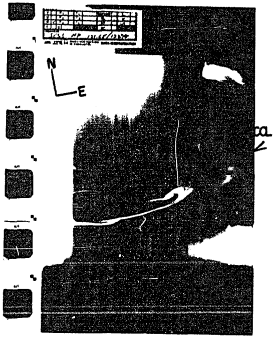

10:25:00
25:10
25:20
25:30
25:40
25:50
10:26:00
26:10
26:20
26:30
26:40
26:50
10:27:00
27:10
27:20
10 SEC
27:30
27:40
27:50
10:28:00
28:10
28:20
28:30
28:40
28:50
10:29:00
29:10

D

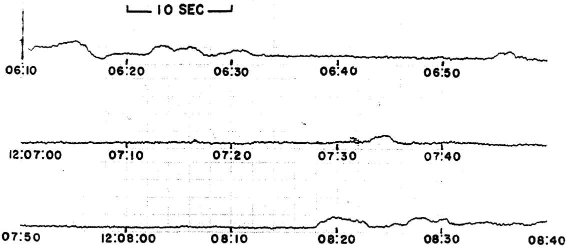
Figure 4.17

Parts A-F present all-sky television data acquired on 26 Feb 1974 during acquisition of the DMSP image shown in Part G. College is located just inside the righthand edge of the DMSP image. Parts A-F show diffuse arcs pulsating slowly within a diffuse background. Part G shows the satellite image of the aurora overhead and west of College near 12:07. Interference from sunlight obscures part of the image at left and just below center at right. Note the large loop structure in the aurora. The intensity trace H (12:06:10 to 12:08:40) shows infrequent pulsations within the region of the arc indicated by the analysis box drawn on Part A.


A
S
W
E
N
B
C
D
E
F


N
E
a

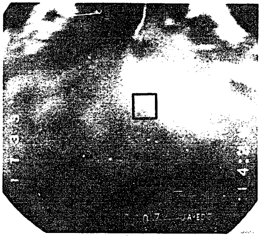
G


10 SEC
06:10
06:20
06:30
06:40
06:50
12:07:00
07:10
07:20
07:30
07:40
07:50
12:08:00
08:10
08:20
08:30
08:40

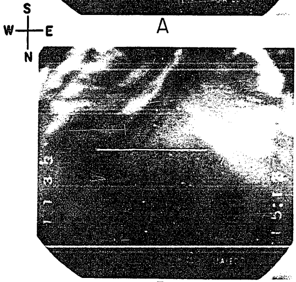
H

Figure 4.18

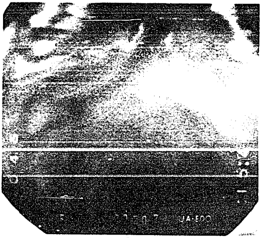
All-sky television data and DMSP image from 20 Feb 1974. Parts A, B, and C (12:14:29, 12:15:12, and 12:15:47, respectively) show a complicated display of pulsating patches over College at the time the satellite passed over the eastern coast of Siberia. The satellite image, D, shows a series of small spirals to the north of a diffuse region. College (at location of arrowhead) is partly obscured by the reflection in the light-shield at the right-hand edge of the picture. The intensity trace E, from 12:12:00 through 12:16:10, shows only a few irregular pulsations.



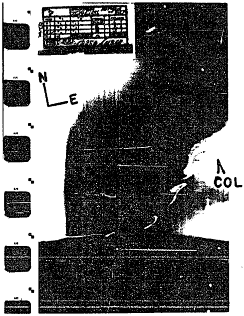
A



B

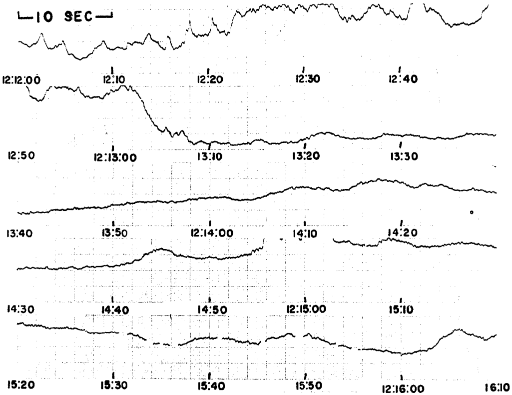


C



N
E
COL

D

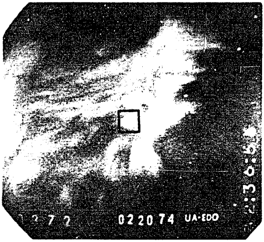


10 SEC
12:12:00
12:10
12:20
12:30
12:40
12:50
12:13:00
13:10
13:20
13:30
13:40
13:50
12:14:00
14:10
14:20
14:30
14:40
14:50
12:15:00
15:10
15:20
15:30
15:40
15:50
12:16:00
16:10

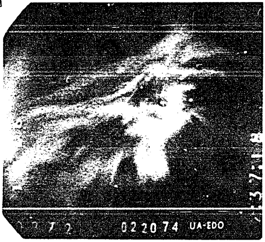
E

Figure 4.19

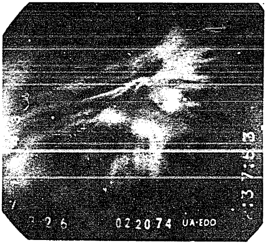
All-sky televison data and DMSP data from 20 Feb 1974. The photographs A, B, and C (12:36:55, 12:37:18, and 12:37:53, respectively) show the display over College at the time of the satellite pass. Only parts of this complicated structure pulsated at any one time. Part D shows the satellite image with Fairbanks and Eielson AFB being visible in the middle of the band of diffuse aurora near the location of the arrowhead. The intensity trace in Part E shows occasional irregular low-amplitude pulsations. (Some sections in the trace were erased because of electronic noise in the televison picture.)



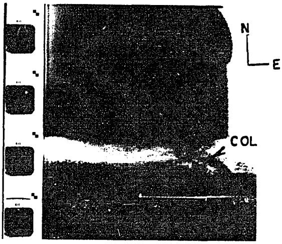
A



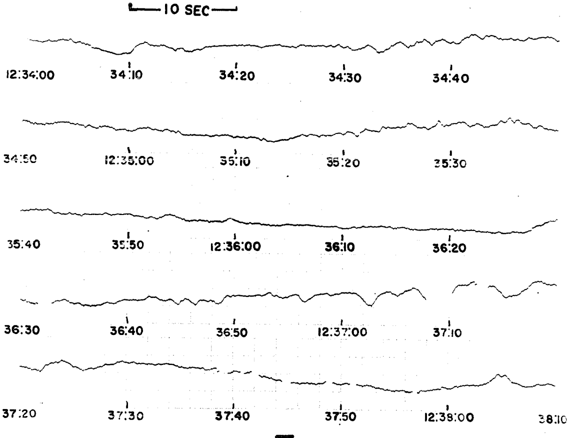
B



C


N
E
COL

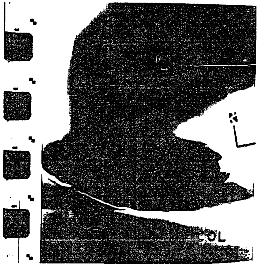
D


10 SEC
12:34:00
34:10
34:20
34:30
34:40
34:50
12:35:00
35:10
35:20
35:30
35:40
35:50
12:36:00
36:10
36:20
36:30
36:40
36:50
12:37:00
37:10
37:20
37:30
37:40
37:50
12:38:00
38:10

E

Figure 4.20

At top a DMSP image and, at bottom, an intensity recording from the all-sky television acquired 12 Dec 1973. The satellite image, obtained near 07:57, shows a relatively bright arc north of College and a diffuse band of aurora overhead. College is located near the arrowhead marked on the image. Although the image is partly obscured by sunlight, discrete aurora can be seen over the Canadian Arctic. The intensity trace shows weak pulsations of 3- to 4-sec duration and 20 to 60 sec apart.


N
E

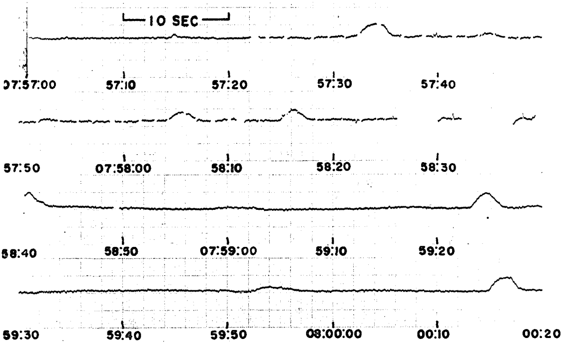
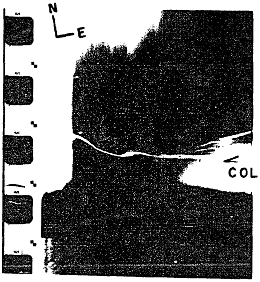

10 SEC
07:57:00
57:10
57:20
57:30
57:40
57:50
07:58:00
58:10
58:20
58:30
58:40
58:50
07:59:00
59:10
59:20
59:30
59:40
59:50
08:00:00
00:10
00:20

Figure 4.21

The DMSP image (top) and the intensity recording from all-sky televison data (bottom) were acquired on 25 Feb 1974 near 09:04. The DMSP image shows a multiple arc structure north of College. The College area is obscured by reflection from the satellite light shield, and similar observation appears at far left. The intensity trace shows irregular pulsations and no indication of high-frequency modulation.


N
E
COL

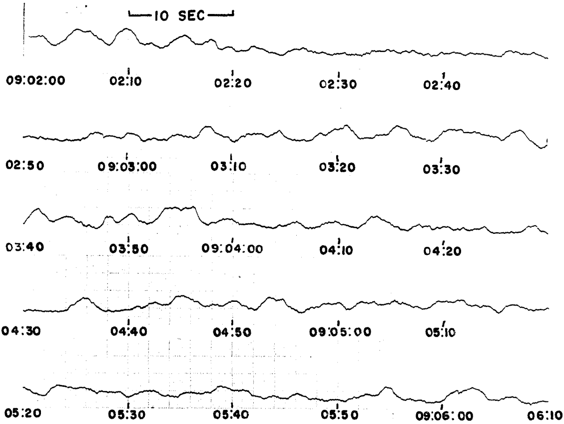
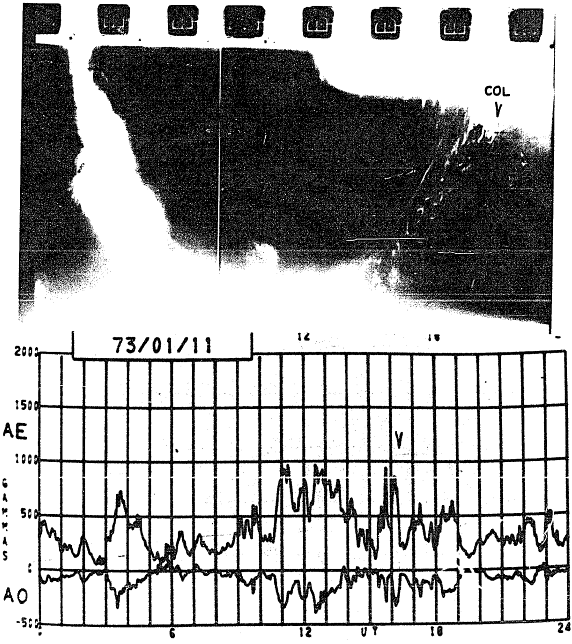

10 SEC
09:02:00
02:10
02:20
02:30
02:40
02:50
09:03:00
03:10
03:20
03:30
03:40
03:50
09:04:00
04:10
04:20
04:30
04:40
04:50
09:05:00
05:10
05:20
05:30
05:40
05:50
09:06:00
06:10

Figure 4.22

Part A contains, at top, the DMSP image acquired near 16:31 on 11 Jan 1973. College is located at upper right, as indicated, within the region of auroral patches readily visible. The direction of the sun is toward the top of the image. The plot of the AE index (at bottom) shows a very disturbed period; the arrowhead marks the approximate time of the satellite pass. The series of 16mm all-sky pictures Part B, shows intensity fluctuations in most of the patches. These apparent fluctuations represent a beat frequency between the frame rate (1 min^{-1}) and the true pulsation frequency. Time, in minutes, is shown at the bottom of each frame.



A

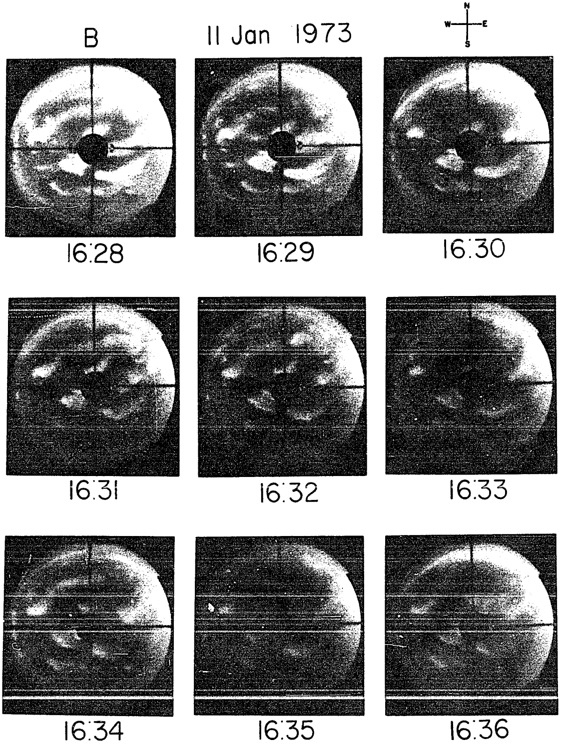
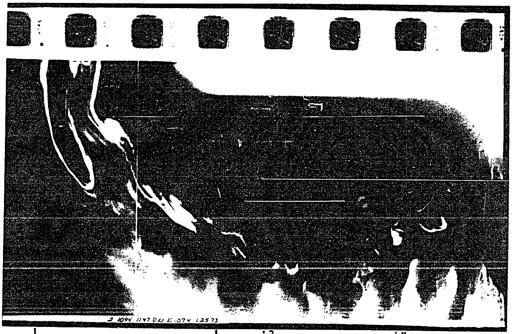

B
11 Jan 1973
N
W
E
S
16:28
16:29
16:30
16:31
16:32
16:33
16:34
16:35
16:36

Figure 5.1

At top is a DMSP image acquired 25 Jan 1973 near 11:25. The direction to the sun is toward the top of the image. The image shows clearly the discrete auroral oval with a large loop in the evening sector and broken up arc segments at the poleward boundary of the diffuse aurora in the midnight sector. The diffuse aurora is also substantially disrupted from a quiet auroral configuration; torch-like structures extend poleward from the region of the diffuse auroral oval. The AE index plot at bottom shows a strong substorm. The satellite pass (marked by arrowhead on the AE index plot) was in the middle of the substorm recovery phase.



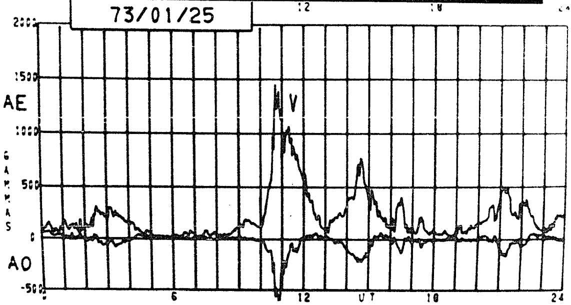

73/01/25
AE
AO
GAMMAS
2000
1500
1000
500
0
-500
6
12
UT
18
24

Figure 5.2

A schematic diagram illustrating the development of an auroral substorm emphasizing the development of pulsating aurora. The pulsating forms are indicated by crosshatched regions superposed on a similar diagram presented by Akasofu (1964).

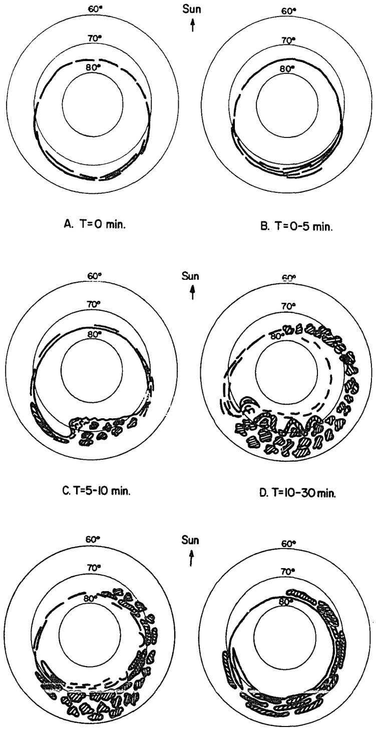

Sun
60°
70°
80°
A. T=0 min.
B. T=0-5 min.
C. T=5-10 min.
D. T=10-30 min.
E. T=30 min.-1 hr.
F. T=1-2 hr.

Figure 5.3

At top a DMSP image acquired on 24 Jan 1973, when the satellite passed north of College near 14:45. The Fairbanks area is visible at the poleward boundary of the diffuse aurora to the right in the picture at the location marked by the arrowhead. Anchorage and the Cook Inlet oil fields are visible at the equatorward boundary of the aurora. The direction to the sun is upward in the image. Thin north-south arcs are visible on the boundary of the torch-like structures. The narrow band of diffuse auroral patches in the morning sector is overhead and east of College in this picture. To the left in the picture two westward-traveling surges can be seen. The AE index at bottom shows a relatively disturbed period lasting for several hours before and after this satellite pass.

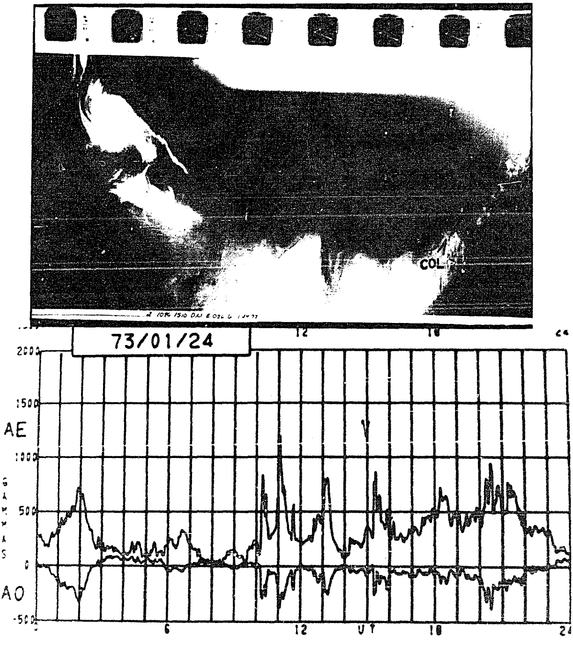
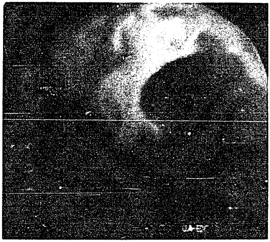
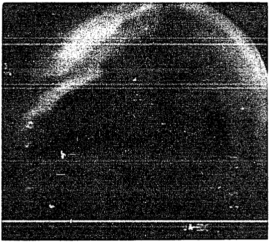

COL
73/01/24
2000
1500
AE
1000
GAMMAS
500
0
AO
-500
6
12
UT
18
24

Figure 5.4

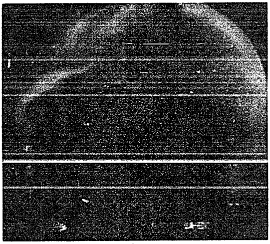
All-sky television data from 21 March 1973. The photographs A, B, and C (09:34:21, 09:35:16, and 09:35:31, respectively) show the westward drift of part of a torch-like structure. The trailing edge is seen to the southwest in these pictures. Photographs B and C also illustrate the streaming of the boundary arc away from the center of the torch.



A



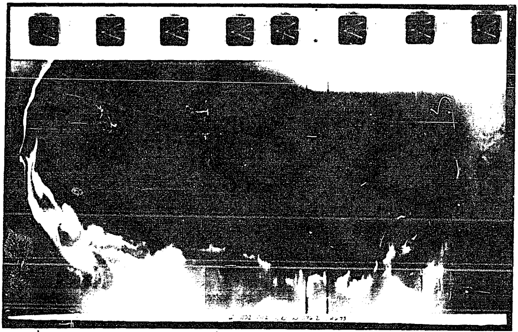
B



C

Figure 5.5

A DMSP image from 26 Jan 1973 acquired when the satellite passed over the auroral oval between 00:45 and 01:05. The bright arc segment north of the diffuse aurora in the morning sector is believed to be an omega band. In the midnight sector the poleward boundary of the oval is composed of discrete auroral arc segments. There is little indication of torch-like structures. The westward-traveling surge appears to be developing into a large loop in the evening sector (left hand side of image). The AE index plot at bottom indicates that the image was acquired during the early recovery phase of a moderate substorm.



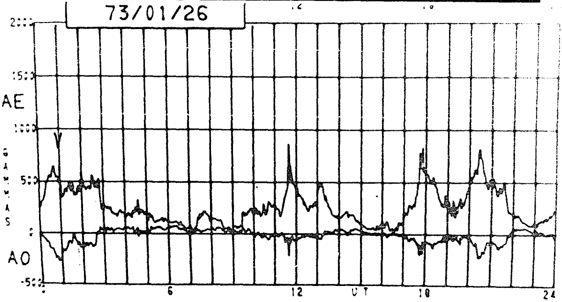
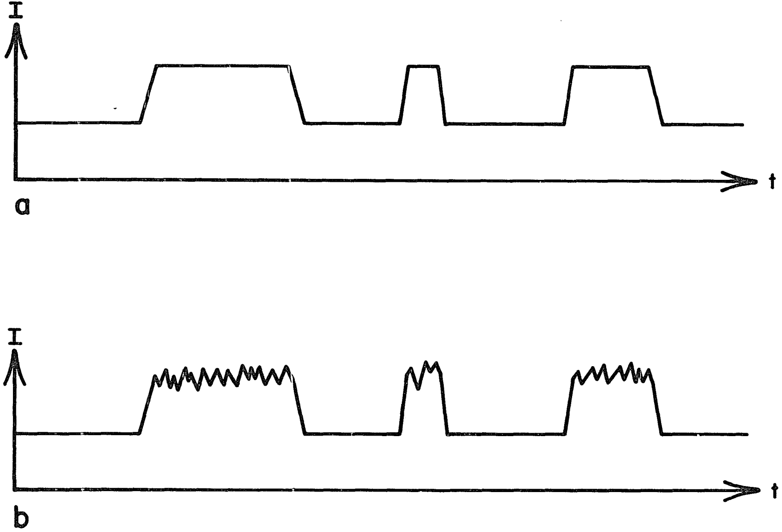

73/01/26
AE
GAMMAS
AO
6
12
UT
18
24

Figure 6.1

Schematic diagram showing the basic pulsations in Part A from a background to a maximum level believed to represent strong pitch angle diffusion. Both the duration of each pulse and the time between are irregular but typically from 2 to 10 seconds. Part B shows the same pulsations but with a high-frequency modulation superimposed on each pulse. The frequency of these modulations is typically from 2 to 4 Hz.


I
t
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I
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b